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COMPUTER SIMULATION OF IN SITU, LOW FREQUENCY, ELECTRICAL
HEATING OF OIL SAND FORMATIONS

by



ALLAN DAVID HIEBERT

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
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ELECTRICAL ENGINEERING

EDMONTON, ALBERTA

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled "Computer Simulation of In Situ, Low Frequency, Electrical Heating of Oil Sand Formations" submitted by Allan David Hiebert in partial fulfilment of the requirements for the degree of Master of Science.

Abstract

The mathematical modeling of electrical and thermal phenomena that occur during in situ, low frequency, electrical heating of oil sand, or other materials with similar electrical properties, is studied. Particular attention was directed toward the modeling of the electrical field at an interface between two media of different electrical conductivities. The finite difference method is used to develop a computer program to simulate, in two dimensions, the mathematical model that was developed.

This computer program is used to study the role of various parameters in determining the final temperature profile after a fixed time period and fixed rate of heating. The parameters studied include the position of the electrodes relative to the overlying and underlying formations, the spacing between the electrodes, and the ratio of the conductivity of the oil sand formation to the conductivity of the surrounding formations.

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Nomenclature

A_{ij}	Coefficient of the (i,j) term of the difference equation.
\bar{B}	Magnetic flux density vector.
C_{ij}	Coefficient of the $(i-1,j)$ term of the difference equation.
\bar{D}	Electrical displacement vector.
\bar{E}	Electrical field vector.
E_E	Electrical energy input.
E_H	Total heat generated.
E_T	Thermal energy stored in the formation.
F_{ij}	Coefficient of the $(i,j-1)$ term of the difference equation.
\bar{H}	Magnetic field vector.
I^n	Total electrical current during the n th time step.
\bar{J}	Electrical current density vector.
M	Volumetric heat capacity.
\dot{Q}	Instantaneous heating rate.
\dot{Q}_{av}	Average heating rate.
R_{ij}	Coefficient of the $(i,j+1)$ term of the difference equation.
S_{ij}	Coefficient of the $(i+1,j)$ term of the difference equation.
T	Temperature
T_0	Initial temperature of the formation.
V^n	Voltage between the electrodes during the n th time step.

d	Distance between the electrodes.
j	Square root of -1.
k_h	Thermal conductivity.
t	Time.
Δt	Length of time step.
V_{ij}	Volume of the (i,j) grid block.
α	Temperature dependence of electrical conductivity.
ϵ	Electrical permittivity.
ψ	Electrical potential.
ρ	Electrical charge density.
ρ_s	Electrical surface charge density.
σ	Electrical conductivity.
σ_{24}	Electrical conductivity at 24°C.
ω	Frequency in radians per second.

1. Introduction

1.1 Electrical Preheat In Situ Method

In northern Alberta there exist large deposits of petroleum in the form of oil sand.¹ The oil in these deposits is too viscous to recover by conventional methods. Commercial developments to date have mined the oil sand in open pit mines, then separated out the petroleum (in the form of bitumen) in large extraction plants. The bitumen is upgraded to "synthetic crude", then piped to a refinery.

As the thickness of the earth, or overburden, above the oil sand formation increases, open pit mining becomes uneconomical. Only about ten percent of the oil sand reserves are recoverable by surface mining.² Thus, there is considerable interest in developing *in situ* (in place) methods of separating out the bitumen. A wide range of possible in situ techniques have been suggested.³

One of the proposed in situ techniques is steam flooding. In the steam flood method an array of injection and production wells are drilled, then steam is pumped down the injection wells and oil and water are pumped up the production wells. A major problem with this method is in developing "communication" between the injection and the production wells. The unheated bitumen is so viscous it blocks the steam and heated, mobilized bitumen from traveling from one well to the other. Various methods have been proposed to develop communication. These include

injection of solvents, formation of emulsions and formation fracturing.¹⁷ The first two methods are designed to reduce the viscosity of the bitumen, and the third method produces a direct channel between wells.

The electrical preheat in situ method proposes that the oil sand formation be heated by passing an electrical current through it, and, once the viscosity has been lowered sufficiently, steam or some other hot fluid be used to drive out the bitumen. The viscosity of bitumen decreases rapidly with increases in temperature.⁴ At natural formation temperatures Athabasca bitumen has a viscosity in the millions of centipoise. If this bitumen is heated to 80°C the viscosity drops to 1000 cp, and if heated to 200°C the viscosity will be about 10 cp. The heat used to raise the temperature of the bitumen is generated right in the oil sand by the electrical current flowing in the connate water. This heating in place overcomes some of the problems usually associated with heating heavy oil formations with steam, such as low thermal conductivity and difficulty directing the applied heat. Electrical heating has seen limited use in secondary recovery of conventional oil fields.⁵ Several patents have been issued on the application of electrical heating to oil sand. Petro-Canada Explorations Ltd. is running a pilot plant investigating the electrical preheat method.⁴

1.2 Means of Investigation

Before pilot plant tests or commercial developments of the electrical preheat method are embarked upon it is necessary to develop an idea of the optimal electrode configuration, heating rates, and heating times. Other than pilot plant or field tests, the study of the electric preheat method may be carried out by three means: analytic calculations, laboratory scale models, and numerical simulation. In all three of these means it is necessary that a mathematical model of the important processes be developed.

The electrical conductivity of oil sand is temperature dependent. This couples the governing thermal and electrical equations. The resulting set of partial differential equations is difficult or impossible to solve analytically for all but the simplest one dimensional cases.

Physical scale modeling of in situ recovery methods is discussed by Farouq Ali and Redford,⁶ and the physical modeling of electromagnetic heating of oil sand is discussed by Vermeulen, Chute, and Cervenán.⁷

It was decided to use numerical simulation to study some aspects of the electrical preheat method. Two other studies reporting numerical simulation of electrical heating of petroleum reservoirs are by Todd and Howell⁸ and El-Feky.⁹ Todd and Howell simulate electrically heating oil sand to several hundred degrees Celsius, while cooling the well bore. El-Feky studied electrically heating conventional

oil reservoirs for secondary recovery. Both of these studies and simulators differ in detail and application from this study.

Numerical simulation may be used as a compliment or alternative to physical scale modeling. Numerical simulation allows easy adjustment of parameters and electrode configurations, but is only as good as the mathematical model on which the simulation is based. Comparison of numerical simulation results and physical scale model results can provide insight into the accuracy of a mathematical model. Physical scale modeling of the electrical heating of oil sand is being done by Vermeulen, Chute and Cervenán⁷ at the University of Alberta, and some of the results of their group are compared to the results obtained by the numerical simulator which is discussed in this thesis.

1.3 Electrical and Thermal Properties of Oil Sand

The electrical conductivity and relative dielectric constant of reconstituted oil sand were measured by Chute, Vermeulen, Cervenán and McVea¹⁰ and correlated to frequency, moisture content, temperature, and density. Similarly, the heat capacity and thermal conductivity of various grades of oil sand were reported by Cervenán, Vermeulen, and Chute¹¹. The applicable results of these two papers are summarized in Table 1.1 and Table 1.2.

Table 1.1 Electrical Properties of Reconstituted Oil Sand at
60 Hz and 24°C.¹⁰

Material	Water (% wt.)	Conductivity (S/m)	Dielectric Constant
Oil Sand A	5.8	1.5×10^{-2}	$4. \times 10^4$
Oil Sand B	3.3	$6. \times 10^{-3}$	$1. \times 10^4$
Oil Sand C	1.3	1.2×10^{-3}	$1. \times 10^3$

Table 1.2 Thermal Properties of Reconstituted Oil Sand and
Other Materials.^{11 18}

Material	Water (% wt.)	Conductivity (W/m-K)	Heat Capacity (J/m ³ -K)
Oil Sand	4.3	1.80	-
Oil Sand	2.1	1.42	-
Oil Sand	1.3	1.35	-
Oil Sand	1.5	-	1.71×10^6
Oil Sand	11.1	-	2.23×10^6
Oil Sand	1.4	-	1.83×10^6
Sandstone	-	.877	1.59×10^6
Limestone	-	1.70	1.86×10^6
Shale	-	1.04	1.87×10^6

The electrical conductivity was found to increase approximately linearly with temperature dependence up to 90°C. The computer program written in this study incorporates this temperature dependence. The electrical conductivity is expressed by

$$\sigma(T) = \sigma_{24} [1 + \alpha(T - 24)] \quad (1.1)$$

where T is in degrees Celsius and σ is in Siemens/meter. The constant α has units $^{\circ}\text{C}^{-1}$ and is the temperature dependence of electrical conductivity. A typical measured value of α for oil sand is $2.3 \times 10^{-2} \text{ }^{\circ}\text{C}^{-1}$.

The author knows of no published data on the temperature dependence of conductivity of oil sand at temperatures above 90°C. Chute et.al.¹⁰ report that above 90°C the conductivity tends to level off, and hence the value of α decreases. In an electrical preheat of an oil sand formation the temperature will remain below 90°C in the bulk of the formation. Near the electrodes the temperature may reach 250°C or higher, but the conductivity of the oil sand will probably be affected by the injection of brine into the formation. Due to the lack of published data the author has assumed that the conductivity increases linearly with temperature, even well above 90°C.

While the thermal conductivity and heat capacity of oil sand may have some temperature dependence, there is no detailed study on such temperature dependence reported in the literature. A few measurements by Cervenán et. al.¹¹

show no marked temperature dependence for the heat capacity of oil sand samples between 20°C and 70°C. The computer program was written so that the temperature dependences of thermal conductivity and heat capacity could easily be included once these dependences are known.

The effects on the electrical preheat process of changing the ratio of the electrical conductivities of the oil sand and surrounding formations is one of the items studied in this thesis. For the study of the effects of changing this ratio the thermal properties of the surrounding formations are assumed to be the same as those of the oil sand. It is also possible to give the surrounding formations different thermal properties than the oil sand.

1.4 The Computer Program "MEGAERA"

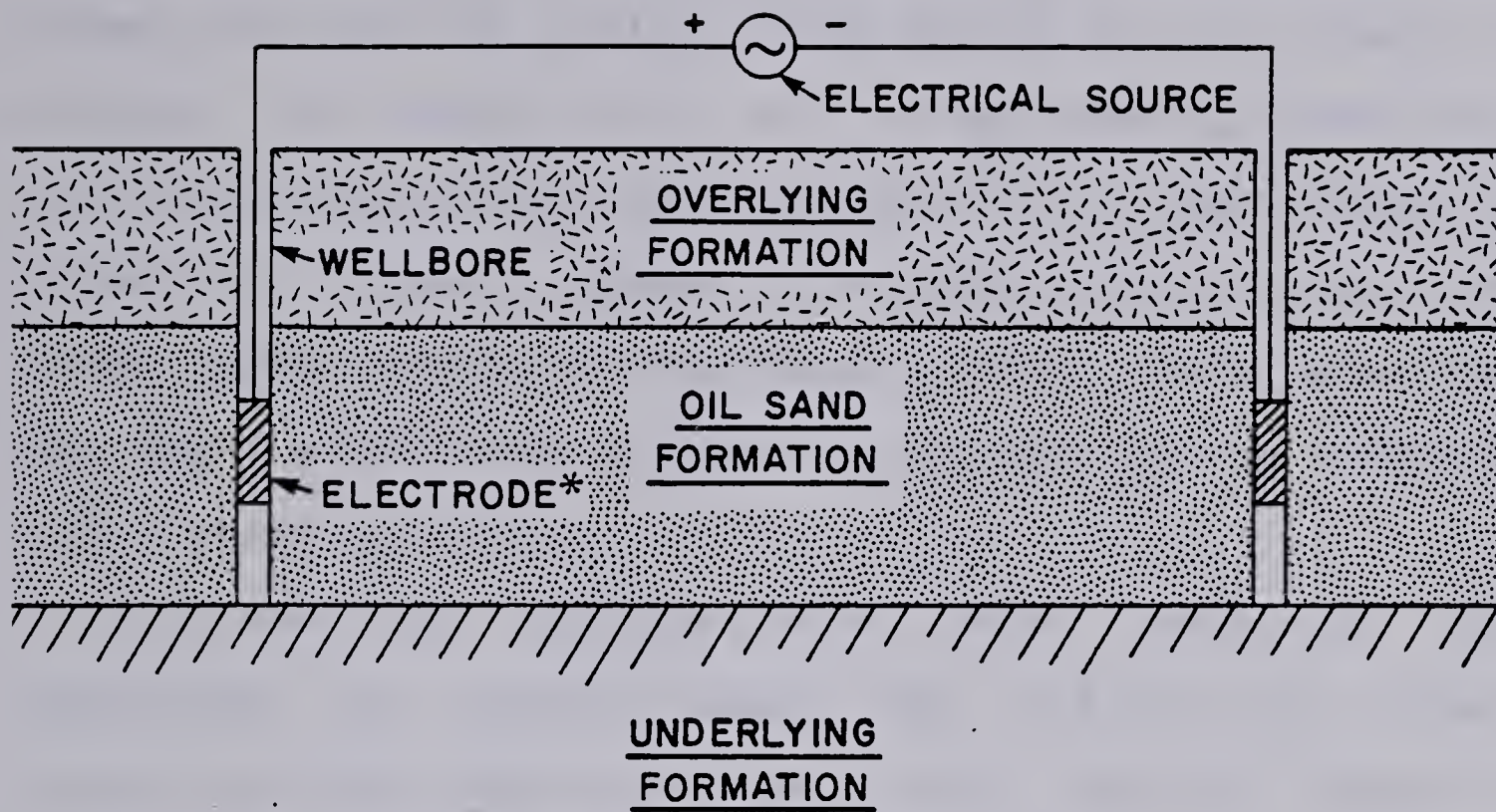
A computer program entitled MEGAERA¹⁶ was written to numerically simulate the electrical conduction heating of oil sands, or other solid materials. The mathematical model and finite difference scheme used in MEGAERA are discussed in detail in the second and third chapters of this thesis. MEGAERA was used to study a variety of electrical heating configurations with different conductivity ratios between the oil sand and the surrounding formations. The results of this study are given in chapter four of this thesis.

Any study, analytic, experimental or numerical, must be limited to some extent. The specification for MEGAERA were based on the type of physical scale modeling being done by

Vermeulen, Chute and Cervenak at the University of Alberta and the experience of the author in writing and using an earlier two dimensional electrical heating simulator.

There were two primary considerations in developing MEGAERA. First, the program had to be able to simulate overburden and underburden of different electrical conductivities than the oil sand. The optimal electrode configuration for heating an oil sand formation is highly dependent on whether the surrounding formations are more or less conductive than the oil sand. Second, the program must be relatively inexpensive to run. For this reason MEGAERA was limited to two dimensions. A typical MEGAERA run takes two to three minutes of C.P.U. time on an Amdahl 470V/7. The time required by a three dimensional program can be conservatively estimated by multiplying the time required by the two dimensional program by the number of grid lines in the third dimension. For a reasonable amount of detail in the third dimension the program would be too expensive to run more than a few times.

While the universe is generally perceived to have three spacial dimensions, it is often convenient and reasonably accurate to model a physical system as two dimensional. In studying electrical heating of oil sand there are two different two dimensional slices of interest. A horizontal (areal) study of the heating pattern in a five spot pattern assumes that the oil sand formation is infinitely thick, but may yield results which are correct for the middle of a



*For clarity the electrodes shown are of the simple cylindrical variety. In actual practise extended electrodes would be used.

Figure 1.1 Typical Vertical Electrode Geometry

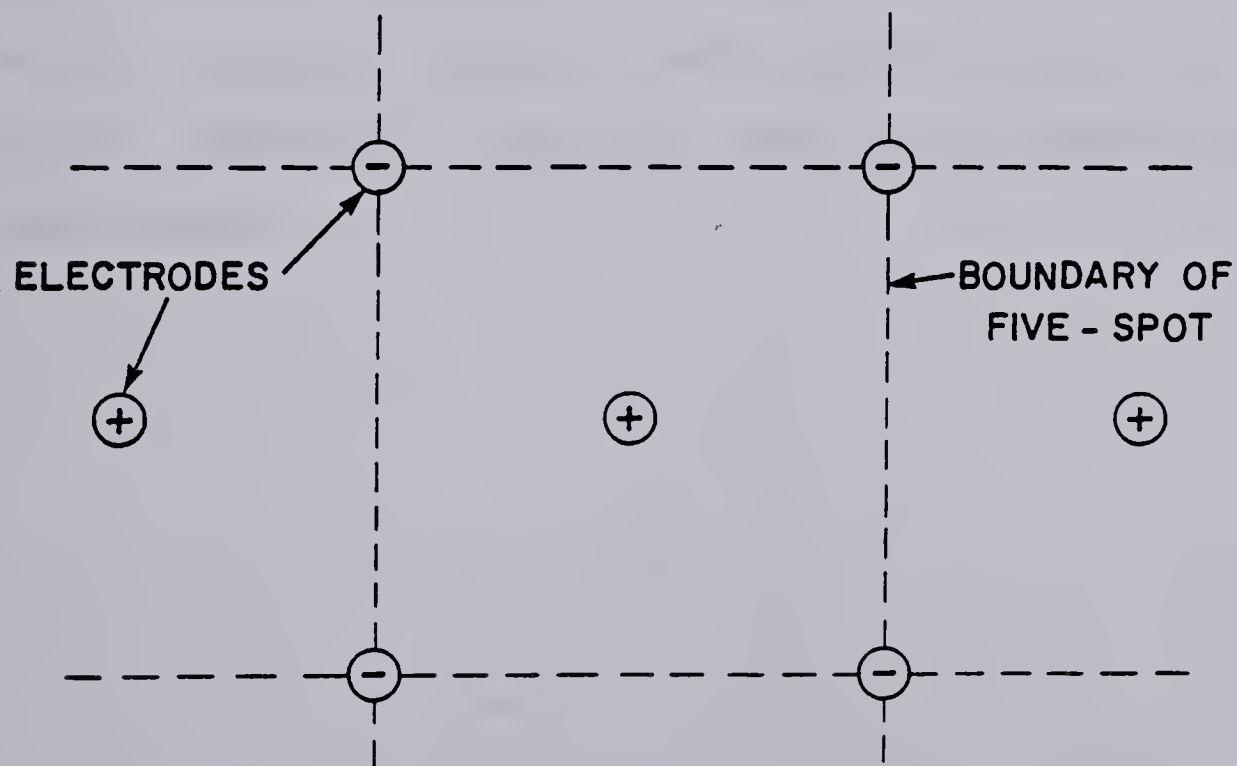


Figure 1.2 Typical Horizontal Electrode Geometry



finite formation. A vertical section studying the heating between two parallel plates allows one to see the effects of changing the conductivity of the surrounding formations. Parallel plates may be approximated in a field test by systems of closely spaced electrodes or by using a more widely spaced system of electrodes in which each electrode has been effectively enlarged by jet cutting the formation with a brine solution.

In modeling configurations with overburden and underburden the energy losses due to electrical current leakage and heat conduction from the oil bearing formation are calculated by MEGAERA. Voltage, current, power and resistance calculation are done at each time step. MEGAERA will automatically scale the applied voltages to produce constant power and constant current heating, if this is desired. A post processor, called MEGAERA.PLOTTER, was written to produce contour and profile plots of the electrical potential, heating rate and temperature at specified times.

2. The Mathematical Model

2.1 Electrical Fields

The basic set of equations of classical electricity and magnetism, first written by Maxwell in 1863, are:^{1 2}

$$\nabla \cdot \bar{D} = \rho \quad (2.1)$$

$$\nabla \cdot \bar{B} = 0 \quad (2.2)$$

$$\nabla \times \bar{E} = -\frac{\partial \bar{B}}{\partial t} \quad (2.3)$$

$$\nabla \times \bar{H} = \bar{J} + \frac{\partial \bar{D}}{\partial t} \quad (2.4)$$

These equations, together with the appropriate boundary conditions, may be used to find the electric field of any electrical heating configuration at any frequency. However, an analytic or numerical solution to Maxwell's equations is difficult, if not impossible, in all but the simplest cases. It is therefore desirable to simplify these equations, dropping terms which are negligible for the frequencies and electrode configurations of interest.

2.1.1 The Quasi-static Approximation

In their paper on physical scale modeling, Vermeulen et.al.⁷ discuss the simplification of Maxwell's equations for various types of electrical heating. The discussion in this section (2.1.1) is drawn from the work of their paper

and from Magid.¹³

Consider the displacement current term in equation (2.4). The ratio of conduction current to displacement current is given by $\sigma/\omega\epsilon$ for time harmonic solutions. For oil sand this ratio is typically greater than one hundred at power frequencies (60 Hz), and does not fall to ten until frequencies of about one megahertz are reached. Thus, for power frequencies the effects of displacement current may be neglected.

The study of the fields of two dimensional, parallel electrode, electrical heating configurations is similar to the calculation of electric fields in lossy parallel plate capacitors. In these types of problems the effects of the time varying magnetic field on the time varying electric field may be neglected if the largest dimension of the problem geometry is much less than a wavelength in the medium. This reduction of Maxwell's equations to the static field equations by neglecting these magnetic and displacement current effects is known as the quasi-static approximation.

The wavelength in oil sand at 60 Hz is between 2000 m and 9000 m,⁷ depending on the water content of the oil sand. As the maximum dimension of a typical electrical heating configuration will probably be less than 200 m, the quasi-static approximation should be valid. If the surrounding formations (overburden and underburden) are also to be modeled, the wavelength in these materials must also

be much greater than the maximum problem dimension and the loss tangent must be much greater than one.

When using the quasi-static approximation the geometry of the electric field is calculated from the static electric field equations. While calculating the fields the potential difference between electrodes is fixed at the peak A.C. value. The time varying electric field is then expressed as:

$$\vec{E} = \vec{E}(x,y,z) \sin \omega t \quad (2.5)$$

where $\vec{E}(x,y,z)$ describes the static field, $\omega = 2\pi f$ where f is the frequency, and t is the time in seconds. The r.m.s. value of the potential difference is used in MEGAERA rather than the peak value. This simplifies the calculation of heating rates and conforms to the practise of stating power line voltages as r.m.s. rather than peak values.

The discussion in the previous paragraph applies to single phase heating. When three phase heating is used the geometry of the electric field of each phase must be calculated separately, using the static field equations and setting the electrodes of the other phases to ground potential. Each of the three electric field geometries thus calculated is then multiplied by the appropriate time variation, which must include the phase differences. Finally, the three fields are added vectorially and the square of the magnitude of the resulting field is averaged over a cycle to get the heating rate. This procedure was not incorporated in MEGAERA, so multiphase heating cannot be

simulated.

2.1.2 Current Continuity Equation

Neglecting the effect of the time varying magnetic field of the electric field yields:

$$\nabla \times \bar{E} = 0 \quad (2.6)$$

Thus, a scalar potential $\psi(x,y,z)$ may be defined.¹⁴

$$\bar{E} = -\text{grad } \psi \quad (2.7)$$

Dropping the displacement current term in equation (2.4) gives

$$\nabla \times \bar{H} = \bar{J} \quad (2.8)$$

Taking the divergence of both sides of equation (2.8) gives

$$\text{div } \bar{J} = 0 \quad (2.9)$$

which states that the current is continuous. As $\bar{J} = \sigma \bar{E}$, where σ is the electrical conductivity, equation (2.9) becomes

$$\text{div}(\sigma \text{ grad } \psi) = 0 \quad (2.10)$$

As the electrical conductivity σ depends on temperature, it will, in general, be a function of position, and equation (2.10) may not be simplified by moving the conductivity term outside the divergence operator.

2.1.3 Electrical Boundary Conditions

Three different types of electrical boundaries are to be modeled in the electrical conduction heating simulation. They are: electrode - conducting material boundaries, insulator - conducting material boundaries, and boundaries between two conducting materials.

Electrodes are simply modeled as regions of constant voltage. If constant power or constant current heating is requested, MEGAERA first calculates the fields assuming constant voltage, then measures the current and scales the electric field to the appropriate case. Electrode - Oil Sand contact impedances were noted by Chute et. al.¹⁰ when measuring the electrical properties of oil sand. A major cause of contact impedance is poor physical contact between the oil sand and the electrode. In the mathematical model used it is assumed that contact impedance has been made negligible by a suitable technique such as the injection of a saline solution near the electrode.

Insulator - conducting material boundaries are modeled in electrostatics as surfaces at which there is no current flow normal to the surface (a homogeneous Neumann boundary condition). Having no current normal to the surface implies that the normal component of the electric field is zero just inside the conducting material. As well as modeling insulating boundaries, this type of boundary condition may be used to model planes of symmetry. Many of the electrode configurations of interest in electrical conduction heating

of oil sand consist of large arrays of electrodes of alternating polarity. The planes of symmetry in the electric field may be used to divide the large array into many small identical cells. The simulation of the heating in one of these small cells is all that is necessary to find the heating in the entire array.

At a boundary between two media of finite conductivity the electric field boundary conditions are:¹⁵

$$\bar{n} \times (\bar{E}_2 - \bar{E}_1) = 0 \quad (2.11)$$

$$\bar{n} \cdot (\bar{D}_2 - \bar{D}_1) = \rho_s \quad (2.12)$$

where \bar{E}_1 , \bar{E}_2 , and \bar{D}_1 , \bar{D}_2 , are the fields in the two media, and where ρ_s is the surface charge at the interface in coulombs per square meter and \bar{n} is a unit vector locally normal to the boundary. These are general boundary conditions for Maxwell's equations and are valid for all frequencies. The boundary conditions may be expressed in terms of the normal and tangential components of the electric field.

Starting with Maxwell's equations, take the divergence of equation (2.4) and substitute in equation (2.1) to get the current continuity equation.

$$\nabla \cdot \bar{J} + \frac{\partial \rho}{\partial t} = 0 \quad (2.13)$$

Writing this equation in its integral form and applying the divergence theorem gives

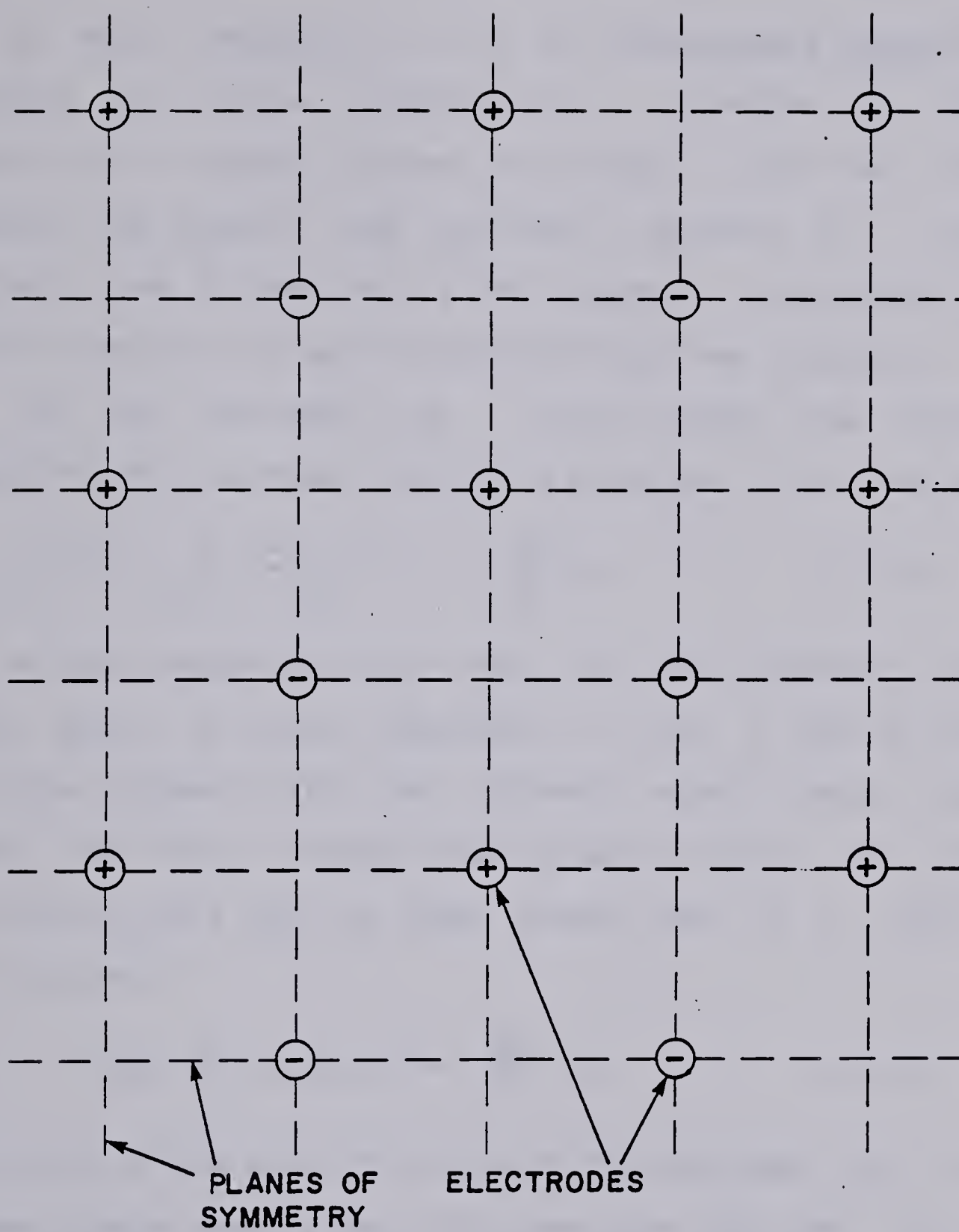


Figure 2.1 Planes of Symmetry in a Five Spot Array

$$\int_S \vec{J} \cdot d\vec{s} = - \int_V \frac{\partial \rho}{\partial t} dv \quad (2.14)$$

To apply equation (2.14) to the boundary between two materials of finite conductivity, consider a small cylindrically shaped volume enclosing a portion of the boundary. One face of the cylinder, denoted S_1 , is in material 1 and is parallel to the boundary. The second face, S_2 , is in material 2 and is parallel to the boundary. The side of the cylinder, S_3 , cuts across the boundary connecting the two faces. Applying equation (2.14) now gives

$$\int_{S_1} \vec{J} \cdot d\vec{s} + \int_{S_2} \vec{J} \cdot d\vec{s} + \int_{S_3} \vec{J} \cdot d\vec{s} = - \int_V \frac{\partial \rho}{\partial t} dv \quad (2.15)$$

Now, let the length of the side of the cylinder shrink toward zero. As both materials 1 and 2 are of finite electrical conductivity, the current density must remain finite, and the integral over S_3 goes to zero. For S_1 and S_2 sufficiently small (but an order larger than S_3), equation (2.15) becomes

$$\sigma_1 E_{n1} \Delta S + \sigma_2 E_{n2} \Delta S = - \frac{\partial \rho_s}{\partial t} \Delta S \quad (2.16)$$

where ΔS is the area of a face of the cylinder, ρ_s is the surface charge density per unit area, and E_{n1} and E_{n2} are the components of the electric field normal to the boundary in materials 1 and 2 respectively. Dividing out the ΔS and assuming a time harmonic field yields

$$\sigma_1 E_{n1} - \sigma_2 E_{n2} = -j\omega\rho_s \quad (2.17)$$

From equation (2.12) and assuming that the electrical permittivity is uniform and isotropic in each material

$$\epsilon_1 E_{n1} - \epsilon_2 E_{n2} = \rho_s \quad (2.18)$$

Substituting in equation (2.17) gives

$$(\sigma_1 + j\omega\epsilon_1) E_{n1} = (\sigma_2 + j\omega\epsilon_2) E_{n2} \quad (2.19)$$

Recall that for the quasistatic approximation to hold $\sigma/\omega\epsilon$ must be much greater than one. Thus, when using the quasistatic approximation the normal component of current is continuous across a boundary between two materials of finite electrical conductivity.

Treating the problem as quasistatic and assuming there are no double layers of charge at the interface, the electric potential must be continuous across the boundary. Thus the boundary conditions used are

$$\sigma_1 E_{n1} = \sigma_2 E_{n2} \quad (2.20)$$

$$\psi_1 = \psi_2 \quad (2.21)$$

In this discussion of the boundary between two materials of finite conductivity it was assumed that the conductivity was discontinuous at the boundary. In an actual oil sand formation the conductivity may change continuously between the oil sand and the overburden or underburden. The electric fields calculated assuming either a sharp, discontinuous boundary, or assuming a continuous transition

over a short distance will be the same except in the transition region. As no data is available describing how the conductivity changes from the oil sand to the surrounding formations, and as the transition distance is likely small compared to the formation thickness, it is assumed that a sharp, discontinuous change in conductivity occurs at the boundary.

2.2 Heat Generation and Transfer

The instantaneous heating rate due to electrical conduction is given by

$$\dot{Q} = \sigma \bar{E} \cdot \bar{E} \quad (2.22)$$

If, when using the quasi-static approximation, the r.m.s. values of the applied voltages are used, then the average heating rate is

$$\dot{Q}_{AV} = \sigma |\bar{E}_{rms}|^2 \quad (2.23)$$

Of the three major heat transfer mechanisms (radiation, convection, and conduction) only conduction is included in the mathematical model. Radiation is negligible as the radiation from a black body at reservoir temperatures would only penetrate a very short distance into the oil sand. Natural convection due to temperature gradients is neglected even though its importance as a heat transfer mechanism in oil sand at the temperatures of interest is unclear. The scale modeling factors developed by Vermeulen et. al.⁷

included only conduction in their derivation. By comparing the results of numerical simulations based on this premise with the results of physical scale model runs some grasp on the accuracy of this mathematical model may be obtained. The treatment of forced convection due to fluid injection or pumping is beyond the scope of this study.

Thus, the equation used to model the heat generation and transfer is

$$M \frac{\partial T}{\partial t} = \nabla \cdot (k_h \nabla T) + \sigma |\bar{E}_{rms}|^2 \quad (2.24)$$

where M is the volumetric heat capacity, k_h is the thermal conductivity, and T is the temperature in Celsius. Note that in the computer program the volumetric heat capacity and thermal conductivity are assumed constant within each formation.

The outer boundaries are assumed to be insulated, no-heat-flow boundaries. If the boundaries are planes of symmetry or actual insulated boundaries this is a good model. However, if the problem to be modeled consists of an oil sand formation surrounded above and below by formations which are much thicker than the oil sand formation (i.e. semi-infinite overburden and underburden) artificial boundaries will have to be introduced to limit the extent of the problem domain. If these boundaries are far enough from the electrodes little current or heat will reach the area near these artificial boundaries.

Different materials in the problem domain may have

different thermal properties. At the boundary between two different materials the temperature and heat flow across the boundary are assumed to be continuous.

3. Numerical Solution of the Model

Finite difference techniques are used to approximate the solution of partial differential equations in many different fields, including oil reservoir simulation, laser-plasma interaction studies, and water flow problems. Finite difference approximations to derivatives were used by L. Euler (1768) and there are currently several textbooks available which explain the finite difference method in detail.^{19 20 21} The error, stability and convergence of the approximation and solution techniques are areas of concern and study when using this method to solve partial differential equations. In this chapter the particular methods used in developing MEGAERA are outlined, and an explanation of how boundary conditions, stability and convergence problems were dealt with is given.

3.1 Differencing of the Current Continuity Equation

The electrical current continuity equation (equation 2.10) may be rewritten (for two dimensions) as

$$\frac{\partial}{\partial x}(\sigma \frac{\partial \psi}{\partial x}) + \frac{\partial}{\partial y}(\sigma \frac{\partial \psi}{\partial y}) = 0 \quad (3.1)$$

The finite difference approximation for the first term of equation (3.1) is given by

$$\frac{\partial}{\partial x}(\sigma \frac{\partial \psi}{\partial x}) \cong \left(\frac{2}{h_i + h_{i-1}} \right) \left[\left(\frac{\sigma_{i+1} + \sigma_i}{2} \right) \left(\frac{\psi_{i+1} - \psi_i}{h_i} \right) - \left(\frac{\sigma_{i-1} + \sigma_i}{2} \right) \left(\frac{\psi_i - \psi_{i-1}}{h_{i-1}} \right) \right] \quad (3.2)$$

See figure 3.1 for details on the grid structuring and labeling.

This approximation (equation 3.2) is "conservative" in that the current flowing out of the left boundary of the grid block (i,j) is equal to the current flowing into the right boundary of the grid block $(i+1,j)$. A symmetric approximation for the second (y direction) term of equation (3.1) is added to equation (3.2) to give an algebraic difference equation at the center of each grid block. Rearranging the terms gives

$$R_{ij} \psi_{i,j+1} + S_{ij} \psi_{i+1,j} + A_{ij} \psi_{ij} + C_{ij} \psi_{i-1,j} + F_{ij} \psi_{i,j-1} = 0 \quad (3.3)$$

where

$$R_{ij} = (\sigma_{i,j+1} + \sigma_{ij}) / [k_j (k_j + k_{j+1})] \quad (3.4)$$

$$S_{ij} = (\sigma_{i+1,j} + \sigma_{ij}) / [h_i (h_i + h_{i+1})] \quad (3.5)$$

$$A_{ij} = -R_{ij} - S_{ij} - C_{ij} - F_{ij} \quad (3.6)$$

$$C_{ij} = (\sigma_{i-1,j} + \sigma_{ij}) / [h_{i-1} (h_i + h_{i-1})] \quad (3.7)$$

$$F_{ij} = (\sigma_{i,j-1} + \sigma_{ij}) / [k_{j-1} (k_j + k_{j-1})] \quad (3.8)$$

The presence of a boundary adjacent to the grid block requires the modification of equations (3.3) to (3.8). If an insulator is in the $(i-1,j)$ grid block, then the boundary condition in the left direction is $\frac{\partial \psi}{\partial n} = 0$. This is

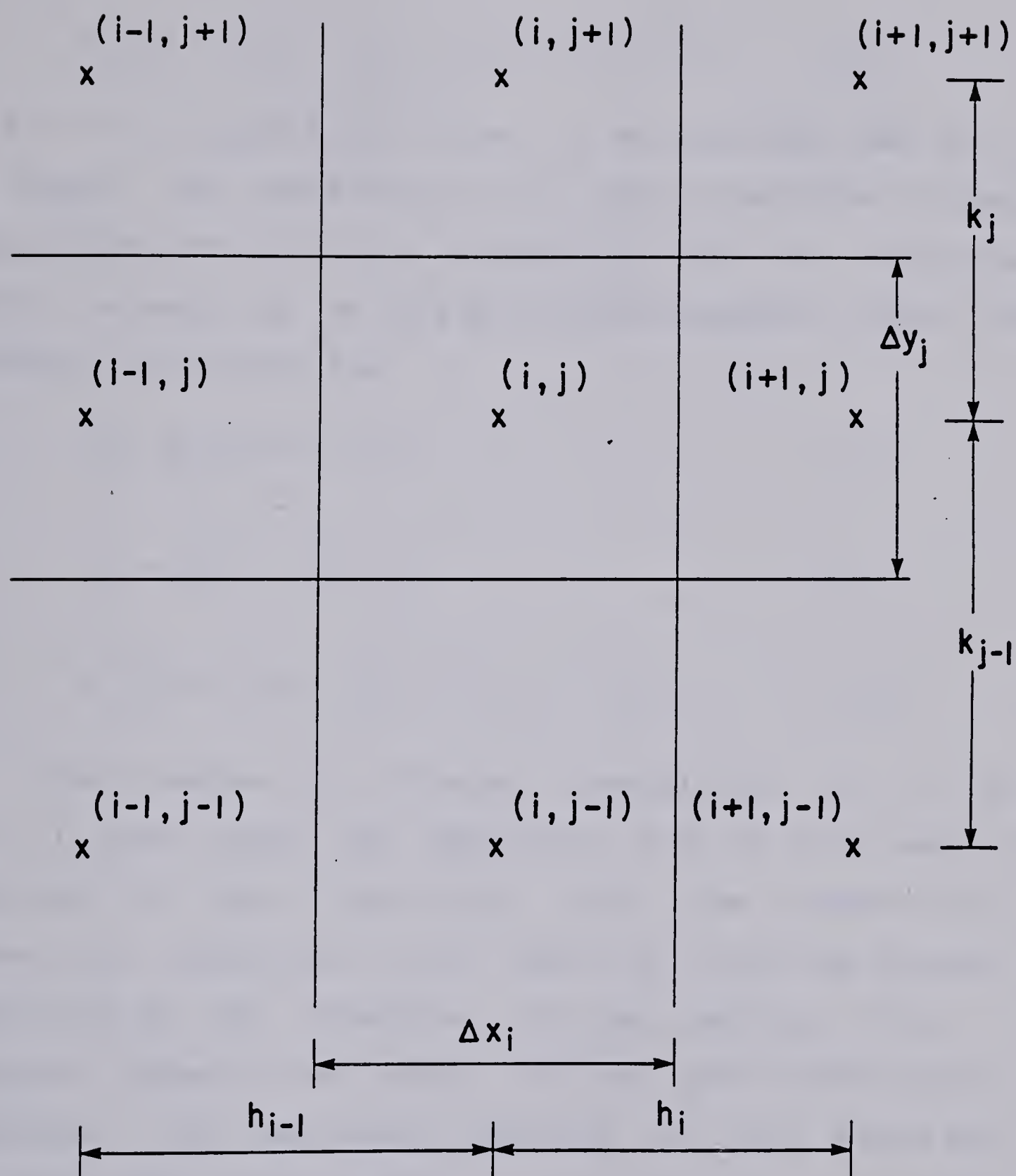


Figure 3.1 Finite difference grid used in MEGAERA showing the locations at which potential, temperature and conductivities are computed.

approximated by setting $\psi_{i-1,j}$ equal to $\psi_{i,j}$. Equation (3.3) becomes

$$R_{ij} \psi_{i,j+1} + S_{ij} \psi_{i+1,j} + (A_{ij} + C_{ij}) \psi_{i,j} + F_{ij} \psi_{i,j-1} = 0 \quad (3.9)$$

If the $(i-1,j)$ grid block is part of an electrode then $\psi_{i-1,j}$ is known. The coefficient of $\psi_{i-1,j}$ must be modified to take into account the infinite conductivity of the electrode (which extends up to the grid block boundary). Thus, the difference equations are

$$C'_{ij} = \sigma_{ij} / [\Delta x_i (h_i + h_{i-1})] \quad (3.10)$$

$$A'_{ij} = -R_{ij} - S_{ij} - C'_{ij} - F_{ij} \quad (3.11)$$

$$R_{ij} \psi_{i,j+1} + S_{ij} \psi_{i+1,j} + A'_{ij} \psi_{i,j} + F_{ij} \psi_{i,j-1} = -C'_{ij} \psi_{i-1,j} \quad (3.12)$$

When a medium of different conductivity is in the $(i-1,j)$ grid block the equations (3.3) to (3.8) must be modified to deal explicitly with the conductivity transition. Equations (2.20) and (2.21) give the boundary conditions at the interface. If the electric field is constant between the center of the grid block and the interface, the continuity condition for the electrical potential (Equ. 2.21) yields

$$(\psi_{ij} - \psi_{i-1,j}) = \frac{\partial \psi_{ij}}{\partial x} \left(\frac{\Delta x_i}{2} \right) + \frac{\partial \psi_{i-1,j}}{\partial x} \left(\frac{\Delta x_{i-1}}{2} \right) \quad (3.13)$$

Figure (3.2) shows a profile of ψ vs x between the grid block centers. Writing equation (2.20) as

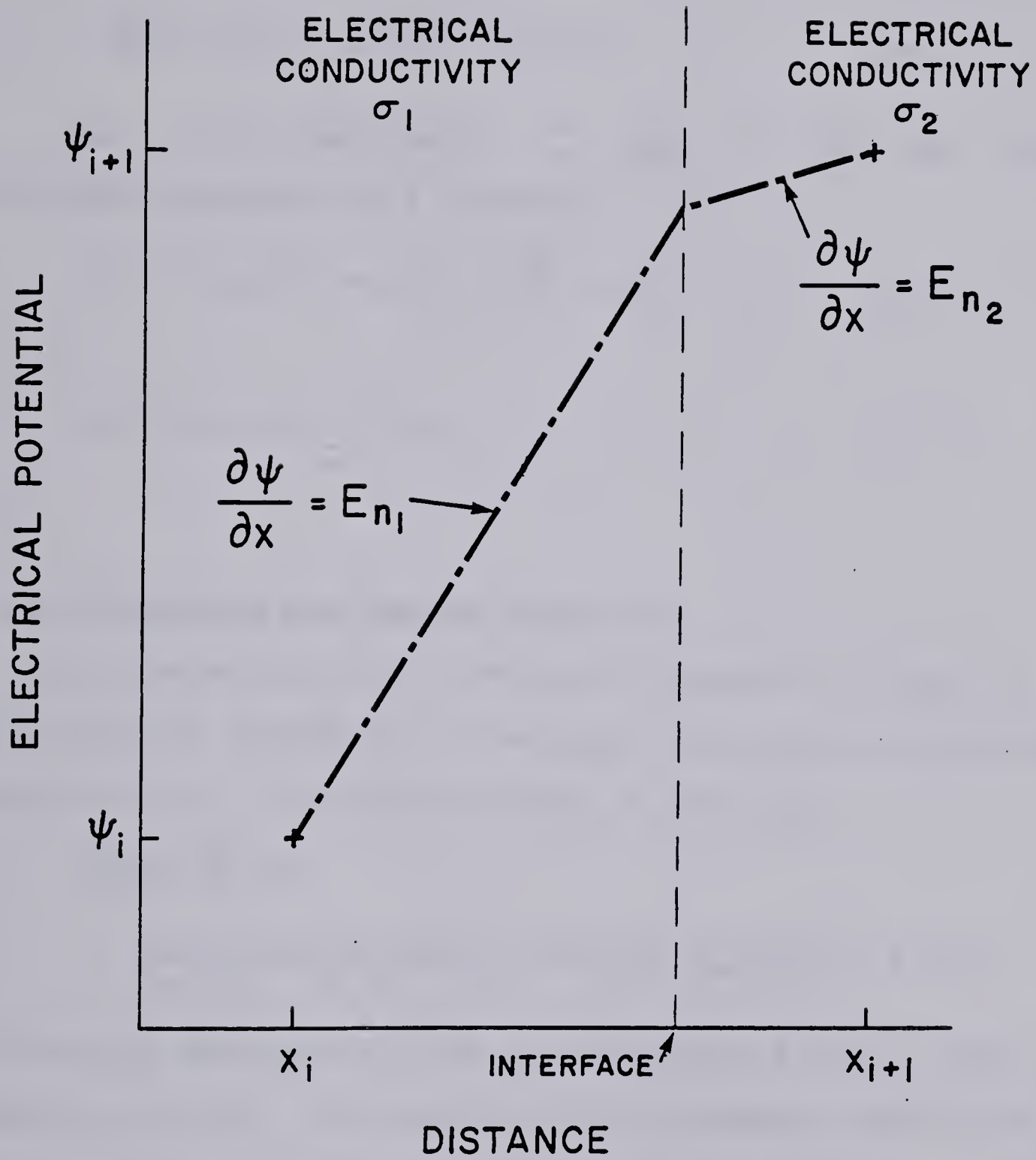


Figure 3.2 Profile of Electrical Potential ψ Across an Conductivity Discontinuity, showing the abrupt change in normal component of the electric field as required for continuity of the normal component of current

$$\sigma_{ij} \frac{\partial \psi_{ij}}{\partial x} = \sigma_{i-1,j} \frac{\partial \psi_{i-1,j}}{\partial x} \quad (3.14)$$

the derivative $\frac{\partial \psi_{i-1,j}}{\partial x}$ in (3.13) may be eliminated.

$$\frac{\partial \psi_{ij}}{\partial x} = (\psi_{ij} - \psi_{i-1,j}) / \left[\frac{\Delta x_i}{2} + \left(\frac{\sigma_{ij}}{\sigma_{i-1,j}} \right) \frac{\Delta x_{i-1}}{2} \right] \quad (3.15)$$

Thus, the coefficients C_{ij} and A_{ij} in the finite difference equation (3.3) become

$$C_{ij}'' = 4\sigma_{ij} / \left[(h_i + h_{i-1})(\Delta x_i + \frac{\sigma_{ij}}{\sigma_{i-1,j}} \Delta x_{i-1}) \right] \quad (3.16)$$

$$A_{ij}'' = -R_{ij} - S_{ij} - C_{ij}'' - F_{ij} \quad (3.17)$$

3.2 Differencing the Thermal Equation

The thermal partial differential equation (2.24) is in many respects analogous to the electrical current continuity equation (2.10). The differencing of the term

$$\frac{\partial}{\partial x} \left(k_h \frac{\partial T}{\partial x} \right) \cong \frac{2}{(h_i + h_{i-1})} \left[\left(\frac{k_{hi,i,j} + k_{hi,j}}{2} \right) \left(\frac{T_{i+1,j} - T_{i,j}}{h_i} \right) - \left(\frac{k_{hi-1,j} + k_{hi,j}}{2} \right) \left(\frac{T_{i,j} - T_{i-1,j}}{h_{i-1}} \right) \right] \quad (3.18)$$

is directly analogous to the differencing of the x term in equation (2.10). The handling of the boundary conditions is also analogous, with constant temperature boundaries corresponding to electrodes and thermal insulators corresponding to electrical insulators.

The time derivative of the thermal equation is approximated by the forward difference

$$M \frac{\partial T}{\partial t} \approx M_{ij} (T_{ij}^{n+1} - T_{ij}^n) / \Delta t^n \quad (3.19)$$

where the superscript indicates the number of the timestep. The heating rate term is also calculated and included in the complete difference equation.

3.3 Solution of the Difference Equations

In solving a set of partial differential equations by the finite difference technique it is desirable to reduce the set of equations by eliminating all but one unknown (one unknown being a single variable unknown at all points in the domain). This may be done before or after differencing the equations. In the electrical heating simulation presented in this thesis, the electrical and thermal equations are coupled non-linearly making the elimination of either the potential or the temperature difficult. For this reason the equations were coupled explicitly: first the electric field was found, then the new temperatures were found. This explicit coupling leads to convergence problems which are discussed in the section on program testing.

The procedure followed by MEGAERA for each time step is as follows:

1. The electrical conductivity of each grid block is updated from the temperature of the grid block at the end of the last time step.
2. The coefficients of the electrical difference equation are found for each grid block.

3. This set of electrical difference equations is simultaneous. With one equation per grid block, a matrix of 2500 rows and columns is formed by MEGAERA if the full fifty by fifty grid is used. This matrix is solved by the Alternating Direction Implicit Procedure. This is an iterative relaxation method, which requires an initial guess at the solution. As the potential does not vary greatly from time step to time step, the potential found in the last time step is used as the initial guess for the potential of this time step and the new potential is found after only a few iterations.
4. With the potential now known, the volumetric heating rate in each grid block is found. MEGAERA calculates the heating rate directly from the potential and cannot output the electric field. The total current passing through the formation between the electrodes is calculated. If constant current or constant power heating is requested, the heating rates are scaled appropriately.
5. The temperatures at the end of the time step are found by solving the thermal equation using the Alternating Direction Implicit method. Despite the similarity of the names, the ADI method is different than the Alternating Direction Implicit Procedure, the former being used for parabolic equations and the latter for elliptic equations.
6. An energy balance is done for the time step. The energy

input, both for the time step and cumulative, is calculated in three different ways, as will be discussed in section 3.4.1. The energy calculations are done for each region of the domain separately, allowing one to find the percentage of energy input to, for example, the overburden and comparing it to the energy input to the oil sand.

MEGAERA was written to allow variable grid widths. The ratio of maximum width to minimum width should not exceed ten in the domain of the problem, with adjacent grid widths being within a factor of two. The program is only two dimensional and the maximum number of grid blocks in each the X and Y directions is fifty. MEGAERA was written in single precision, which on the Amdahl 470 is 32 bit, hexadecimal format floating point arithmetic. Using the full fifty by fifty grid, MEGAERA uses approximately 1.9 seconds of C.P.U. time per time step on an Amdahl 470V/7, and requires about 110 pages of virtual memory. Thus, a typical eighty time step run will require about two and a half minutes of C.P.U. time.

3.4 Testing of MEGAERA

A large simulation code may be tested in several ways. Internal checks, such as energy balance calculations, give one indication of the accuracy of the program. Analytic solution of simple problems may be possible, and the results of simulating these problems may be compared to the analytic

solution. Physical modeling of more complex problems may be possible and numerical simulation results may be compared to physical model results. Finally, one may check that alteration of the problem grid and scale do not significantly affect the results produced by the simulator. All of these methods were used to test MEGAERA.

3.4.1 Energy Balance

The cumulative electrical energy input at the electrodes is found from

$$E_{\epsilon}^n = E_{\epsilon}^{n-1} + V^n I^n \Delta t^n \quad (3.20)$$

where E_{ϵ}^n denotes the total electrical energy input up till the end of the n th time step, V^n and I^n are the voltage and current respectively during the n th time step, and Δt^n indicates the length in seconds of the n th time step.

The cumulative electrical energy that is converted to heat is found by integrating the volumetric heating rate over the volume and time:

$$E_H^n = E_H^{n-1} + \sum_{i,j} \dot{Q}_{AV,i,j}^n V_{i,j} \Delta t^n \quad (3.21)$$

where E_H^n is the cumulative energy converted to heat at the end of the n th time step, $V_{i,j}$ is the volume of (i,j) grid block and $\dot{Q}_{AV,i,j}^n$ is the volumetric heating rate in the grid block during the n th time step.

The total heat energy stored in the temperature rise of the formation is found by summing the product of temperature

rise, volumetric heat capacity and volume of each grid block:

$$E_T^n = \sum_{ij} (T_{ij}^n - T_o) M_{ij} v_{ij} \quad (3.22)$$

All three calculations of the energy input to the formation should yield the same quantitative result. The computer program calculated E_E , E_H , and E_T for each timestep that was output. Comparing E_E and E_H , the differences between both the cumulative and the incremental values of these quantities were under one percent for all production runs of MEGAERA. The differences were greatest for the first time step, usually about .5 to .7 percent, and decrease as the run progressed. By the eightyth time step both cumulative and incremental differences were below one quarter percent. The difference between E_H and E_T was usually less than 0.1 percent. These figures are taken from production runs (Run No.s 10 - 20), where the electrical conductivity varied from one region to the next by up to a factor of ten.

3.4.2 Comparison with Analytic Results

A number of MEGAERA runs were done for simple one dimensional problems whose solutions could be found analytically. Initially the temperature dependence of electrical conductivity was set equal to zero, uncoupling the electrical equations from the thermal equation. The problem geometry consisted of two materials of different

conductivity in series. The results showed that the potential solver, constant current or power scaling, heating rate calculator, and temperature solver were working properly, at least for one dimensional problems. In these tests the calculated values agreed with the analytic solutions to within .1 percent. The problems were solved using grids of varying grid width and differing overall scale (i.e. maximum dimensions).

It is also possible to analytically solve a one dimensional problem involving electrical conductivity which varies with temperature. If a rectangle of homogeneous material is placed between two parallel plates (and the remaining four sides are insulated) and a constant voltage is applied between the plates, the electric field will remain constant between the plates. As the conductivity rises with temperature so will the heating rate. The temperature at any time may be found by solving the integral equation

$$T = \frac{V^2 \sigma_{24}}{M d^2} \int_0^t [1 + \alpha(T - 24)] dt + T_0 \quad (3.23)$$

where d is the distance between the plates, and V is the applied voltage (r.m.s. value). This integral equation may be solved by use of a Laplace transform. The solution is^{22 23}

$$T(t) = \left[\frac{1}{\alpha} + (T_0 - 24) \right] \exp\left(-\frac{V^2 \sigma_{24} \alpha}{M d^2} t\right) + 24 - \frac{1}{\alpha} \quad (3.24)$$

Runs was carried out modeling this problem. When the maximum

allowed temperature change per timestep was three percent, the difference between the computer solution and the analytic solution was one half of one percent after a temperature rise of 230°C . If the maximum allowed temperature change per timestep was increased to ten percent, this difference, after a similar temperature rise, was five percent. The former case required roughly three times the C.P.U. usage of the latter case.

The difference between the analytic solution and the computed temperatures is due to the explicit coupling of the electrical and thermal equations. The electrical field and heating rates are held fixed in a time step, resulting in a conservative approximation to the actual heating. As the conductivity increases with temperature, the calculated heating rate will always be less than its actual value. The error induced by this problem is negligible if the maximum allowed temperature change per timestep is five percent or less.

3.4.3 Comparison with Physical Models

MEGAERA was used to simulate a physical model run which was carried out by J. Fearn and A. Vogan of the Applied Electromagnetics group at the University of Alberta. The geometry of the physical model was a scaled down version of figure 4.2. The model consisted of eighteen inches (457 mm) of underlying sand covered by seven and three quarters inches (197 mm) of low conductivity oil sand, which in turn

is covered by six inches (152 mm) of overburden sand. The spacing between the electrodes was thirteen inches (330 mm) and the third dimension of the model, i.e. the thickness of the two-dimensional slice, was four inches (102 mm). The electrodes were constructed of one quarter inch (6 mm) copper plate and were two inches (51 mm) high and their lengths were equal to the thickness of the two-dimensional slice, i.e. four inches (102 mm). The electrodes were positioned so the right electrode was forty percent in the overburden sand and the left electrode was forty percent in the underlying sand, the remainder of each electrode being in the oil sand.

The underlying and overburden formations in the scale model were modeled using packed sand whose moisture content had been adjusted so the conductivity of the packed sand (density of 1.8 gm/cm^3) was $7.4 \times 10^{-3} \text{ S/m}$. The oil sand was modeled with oil sand whose conductivity when packed (density of 2.0 gm/cm^3) was $2.0 \times 10^{-3} \text{ S/m}$.

The scale model was heated by passing a constant current of .183 A between the electrodes for 3605 seconds. The initial temperature of the model was 22°C ($\pm .8^\circ$). After the run was completed the thermal properties of the sand and oil sand used in the model were measured. The thermal conductivity of the underlying and overlying sand was 1.56 W/K-m and its volumetric heat capacity was $1.37 \times 10^6 \text{ J/K-m}^3$. The thermal conductivity of the oil sand was 1.61 W/K-m and its volumetric heat capacity was $1.8 \times 10^6 \text{ J/K-m}^3$.

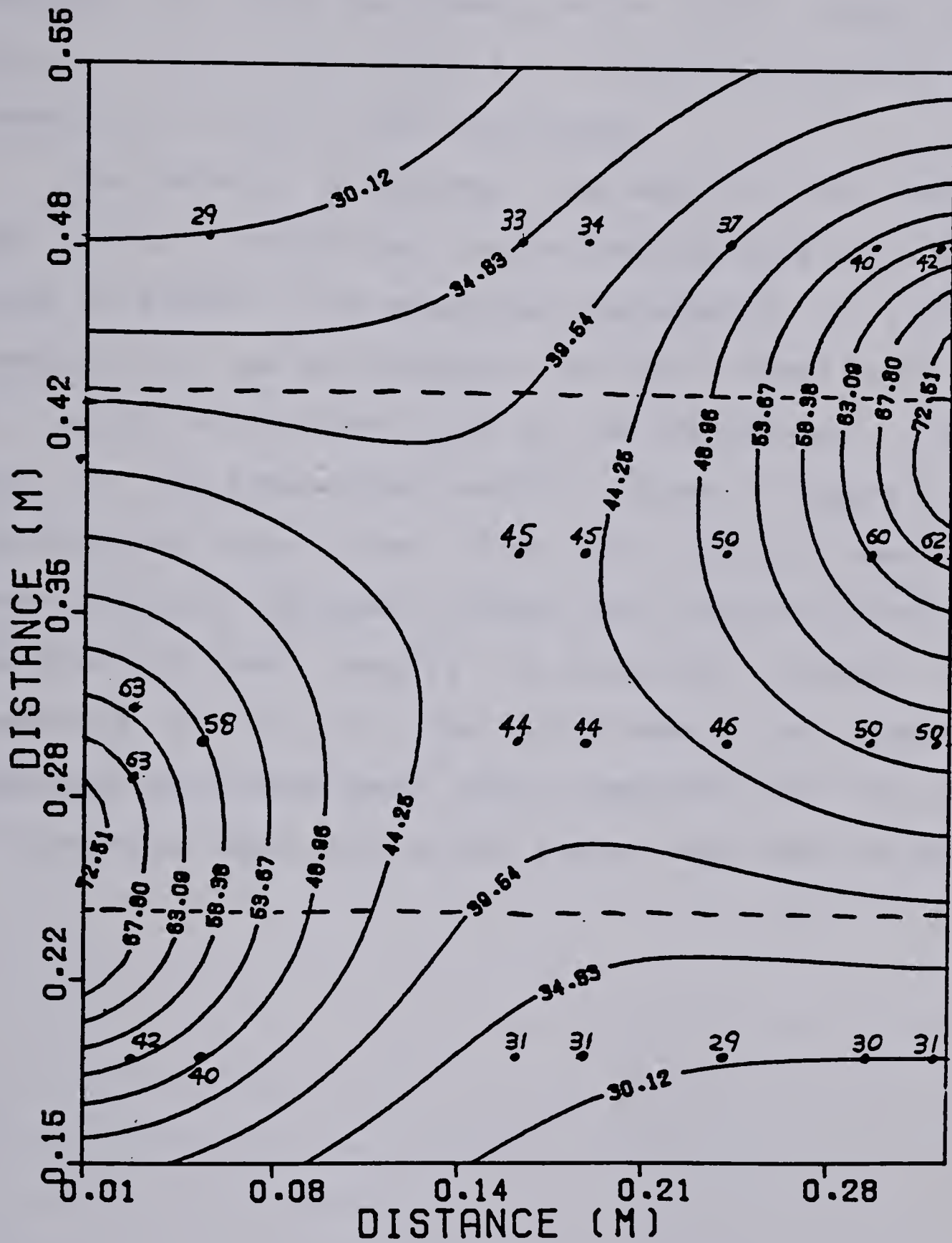


Figure 3.3 Computer calculated and measured temperatures for the physical model run. The contour plots are computer generated and the measured values are written on top.

The simulation was carried out with the thermal conductivity of the electrodes initially set to that of oil sand, and secondly to a value ten times greater. This change caused only a slight change in the final temperature profile in the immediate vicinity of the electrodes.

The geometry, dimensions, sand and oil sand electrical and thermal properties, and the heating type and time were input to MEGAERA. The temperature dependence of electrical conductivity was not measured, but was assumed to be 0.0229 K^{-1} , which is a typical value at low frequencies⁷. A contour plot of the simulation results is given in figure 3.4 with the measured temperatures from the physical model noted where measured. Agreement between the simulation results and the physical model results is excellent, except in the immediate vicinity of the electrodes. The measured and computed resistances were also compared and the percent difference between the two was always less than two percent.

4. Results of MEGAERA Simulation Runs

There are a large number of variables which affect the electrical heating of an oil sand formation. These include the electrical and thermal properties of the oil sand and surrounding formations, the length and thickness of the electrodes, the spacing between electrodes, the thickness of the oil sand, and the rate of heating. In studying the effects of varying one of these variables the other variables must be held fixed.

The initial studies done with MEGAERA were on the effects of different ratios of electrical conductivity of oil sand to that of the surrounding formations, and on the effect of changing the spacing between the electrodes.

4.1 Effects of the Electrical Conductivity Ratio

The author has conducted a series of runs of MEGAERA in which the physical dimensions, thermal properties and heating rates were held fixed, but the electrical conductivities of the oil sand and surrounding formations were varied. The purpose of the series of runs was to determine which of two electrode configurations produces the most favourable temperature distribution for a given ratio between the electrical conductivity of the oil sand and that of the surrounding formations. The problem geometries, labeled configuration A and B, are shown in figures 4.1 and 4.2. In all runs constant power heating of eight kilowatts

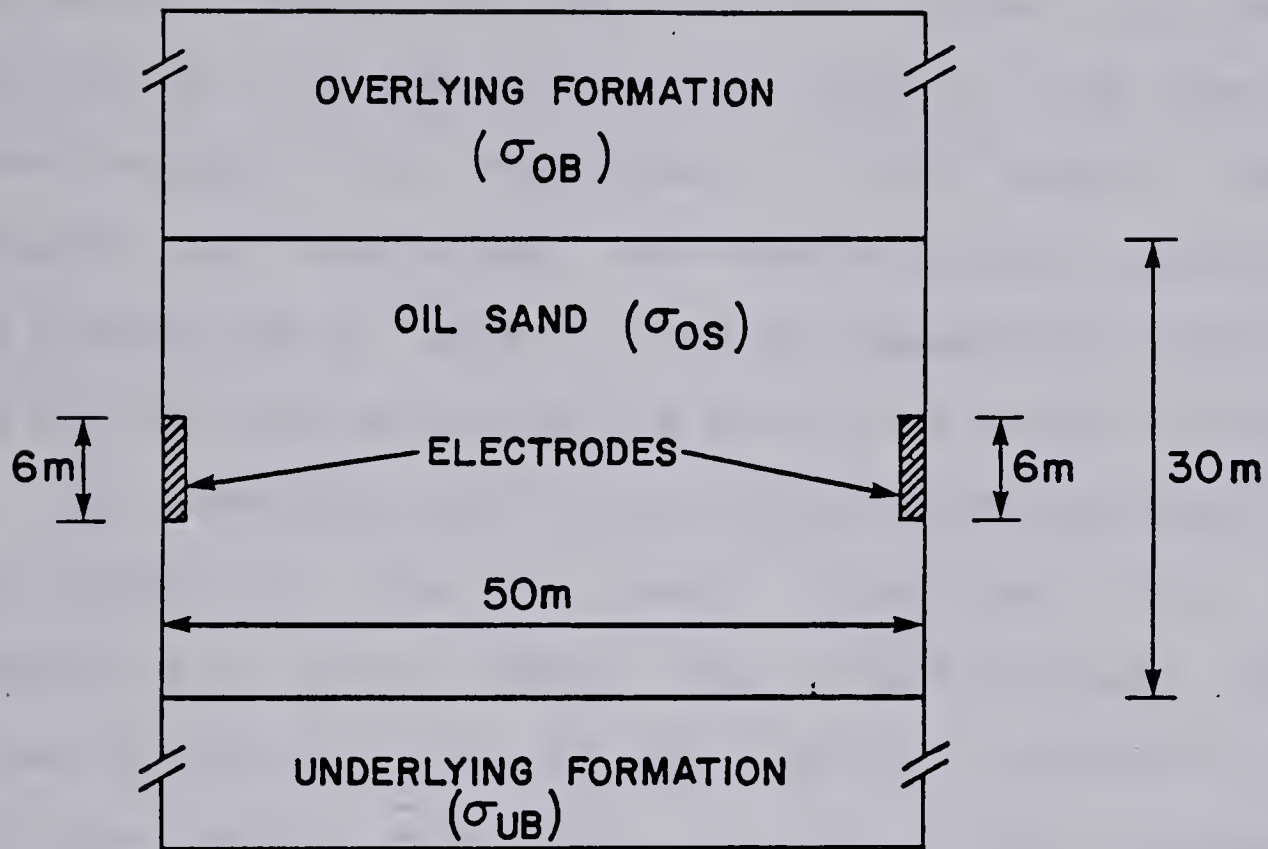


Figure 4.1 Heating Configuration A.

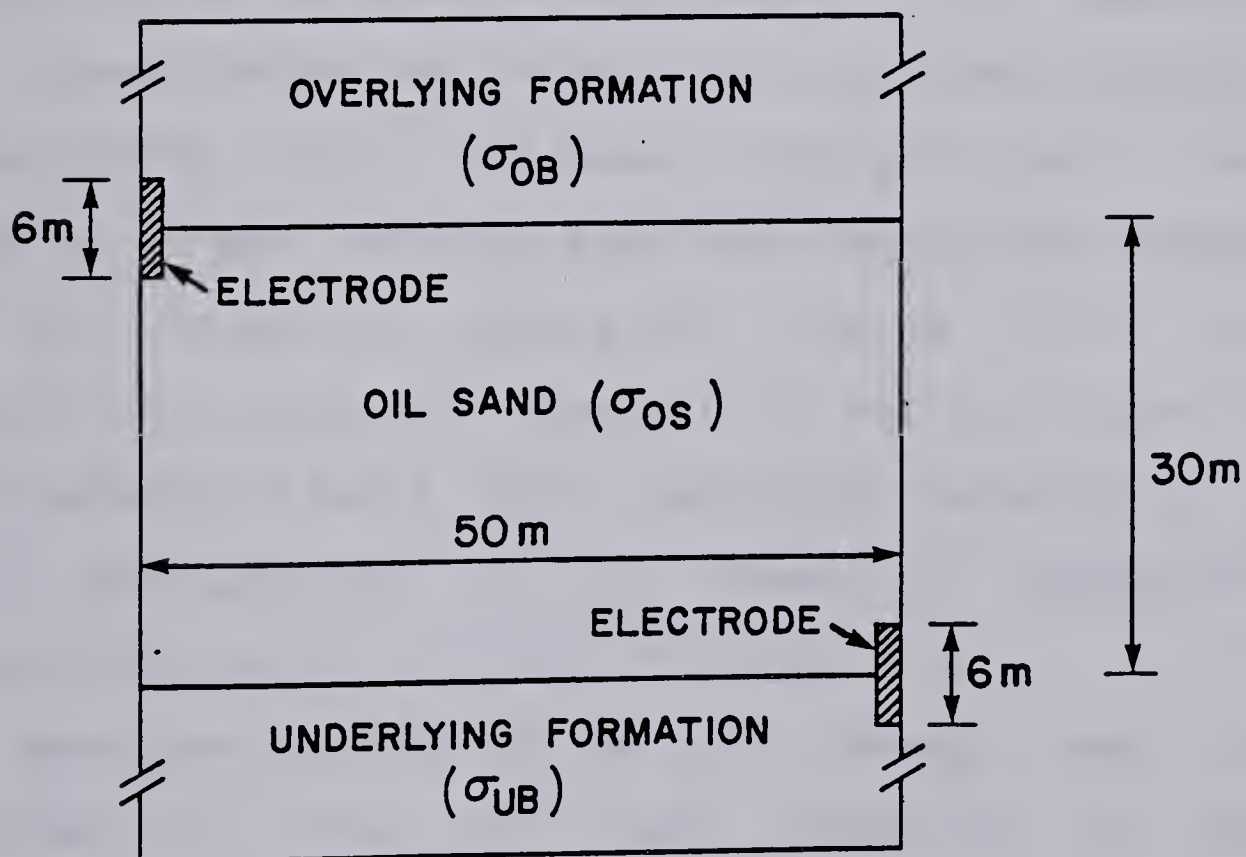


Figure 4.2 Heating Configuration B. The thicknesses of these two dimensional geometries are set to one meter for resistance and power calculations.

per meter length of the parallel plate electrodes was applied for a period of one year. Thus, all the runs had the same heating rate regardless of the actual resistance between the electrodes. The results of this series of runs are summarized in Table 4.1 and the temperature plots at the end of the heating period are given in Figures 4.3 to 4.9.

In configuration A (i.e. the electrodes positioned in the middle of the oil sand formation) the maximum temperature, which occurs near the electrodes, increases linearly with the ratio of the electrical conductivities of the surrounding formations to that of the oil sand. (This ratio, electrical conductivity of overburden and underburden to electrical conductivity of oil sand, shall hereafter be referred to as the conductivity ratio.) The temperature in the formation mid way between the electrodes dropped as the conductivity ratio increased. Configuration B had the opposite trend with the electrode temperature dropping and the mid formation temperature rising with increased conductivity ratio. For conductivity ratios greater than two configuration B had a more desirable temperature profile than configuration A. A graph of temperature vs. conductivity ratio is given in figure 4.10.

When the fraction of the total energy input that is retained in the oil sand formation is computed, configuration A is superior to configuration B even with the conductivity ratio as high as five. With a conductivity ratio of one half, configuration A heating will retain about

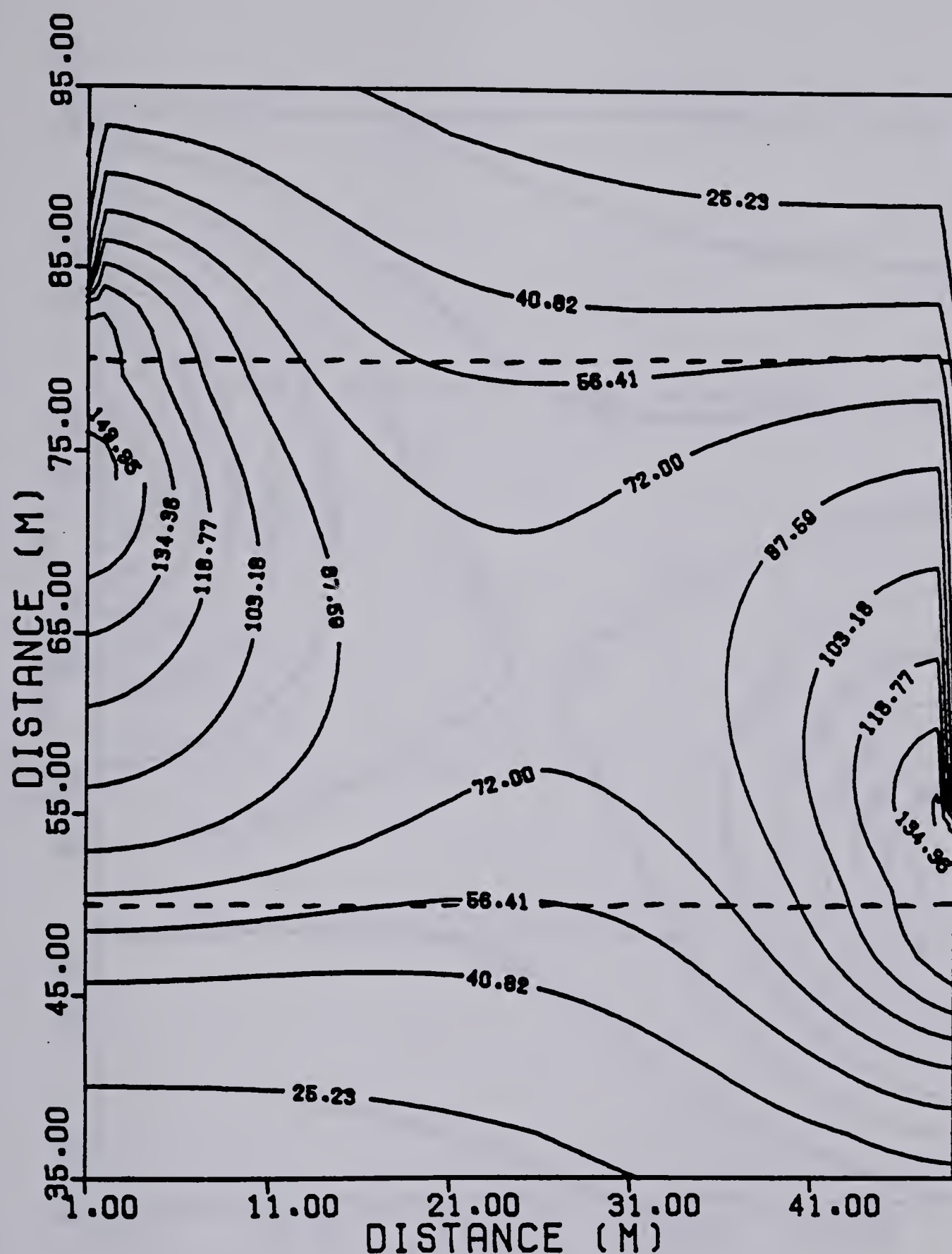


Figure 4.3 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 10, configuration B, with an electrical conductivity ratio (overburden, underburden/oil sand) of 10.

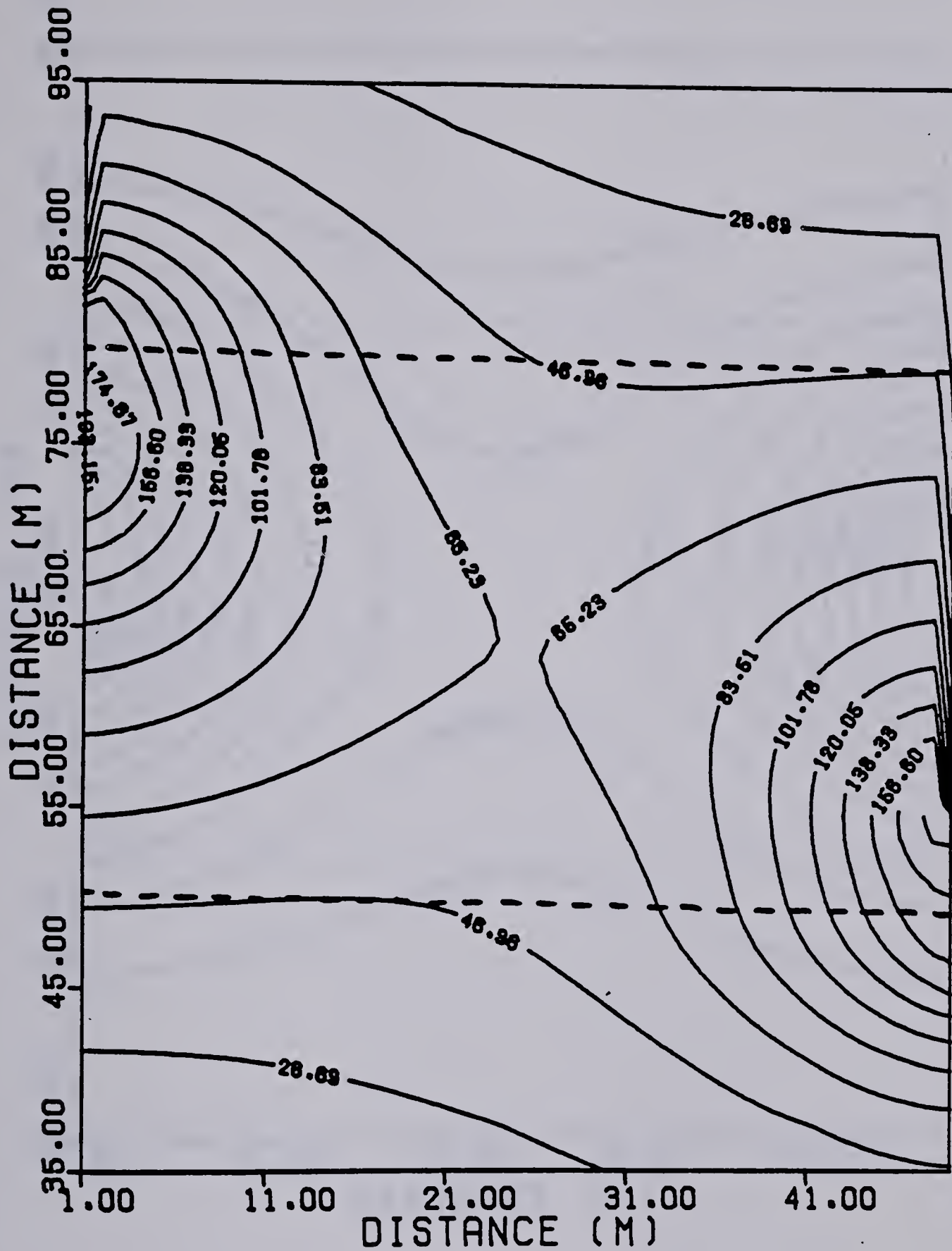


Figure 4.4 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 12, configuration B, with an electrical conductivity ratio (overburden, underburden/oil sand) of 2.

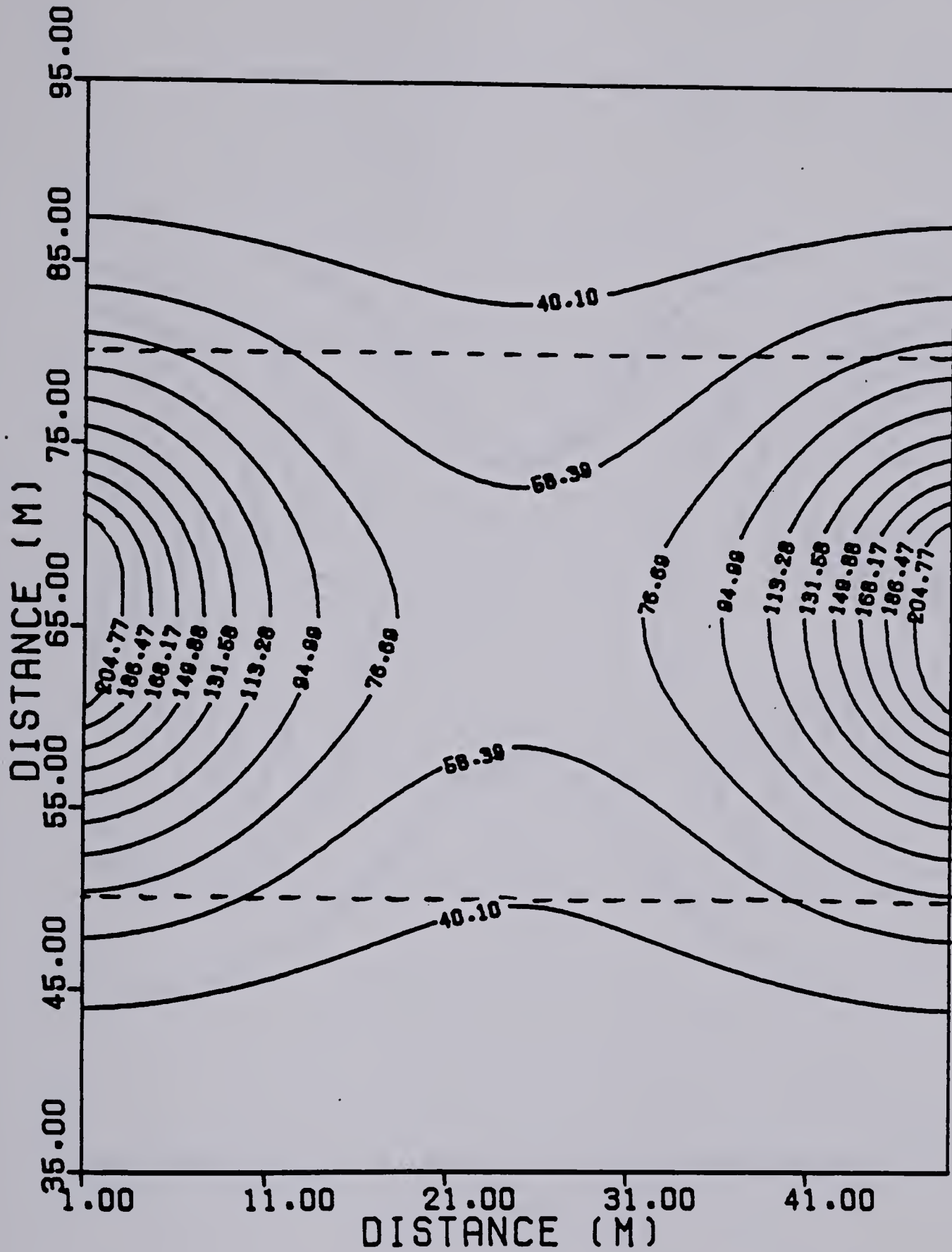


Figure 4.5 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 18, configuration A, with an electrical conductivity ratio (overburden, underburden/oil sand) of 2.

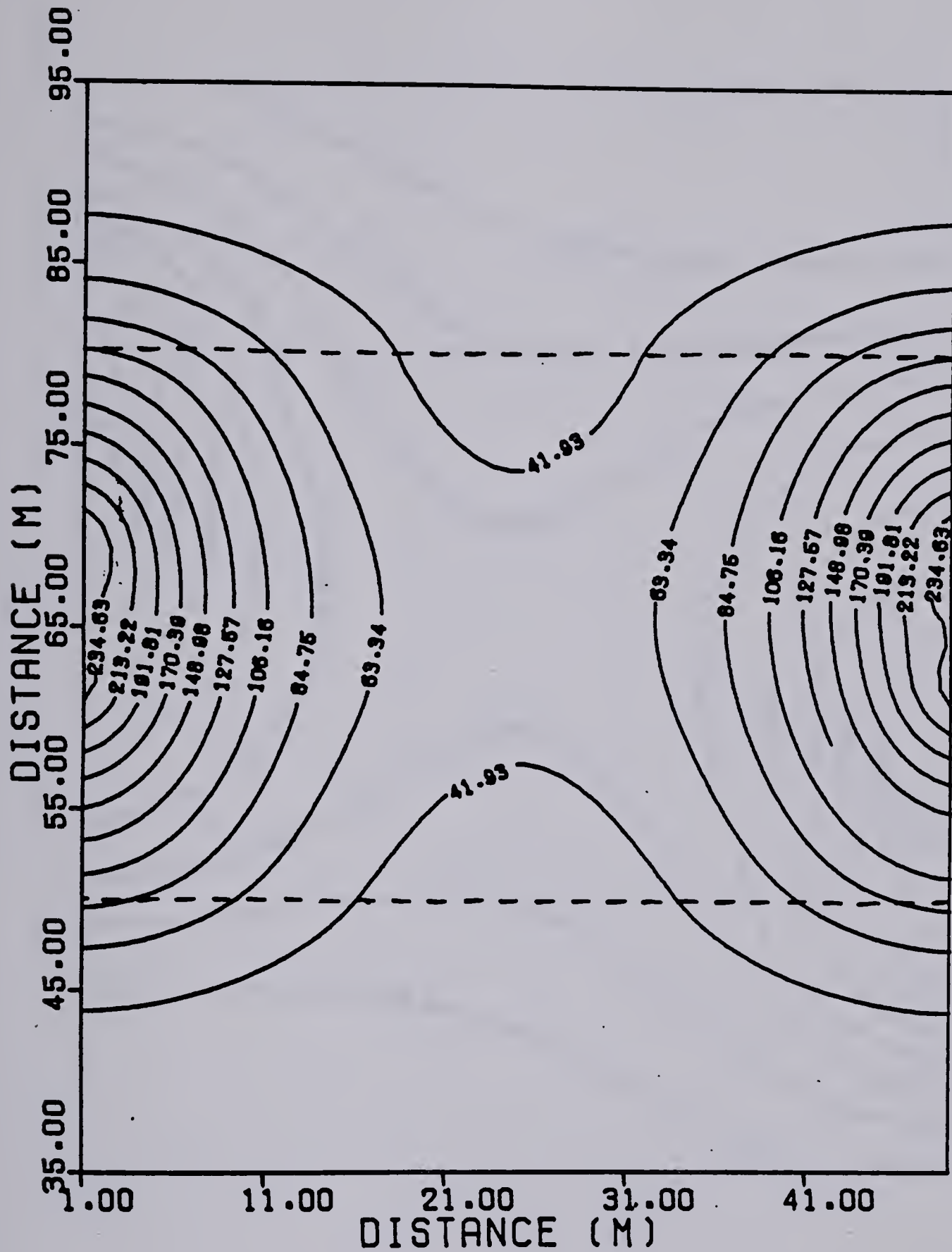


Figure 4.6 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 19, configuration A, with an electrical conductivity ratio (overburden, underburden/oil sand) of 5.

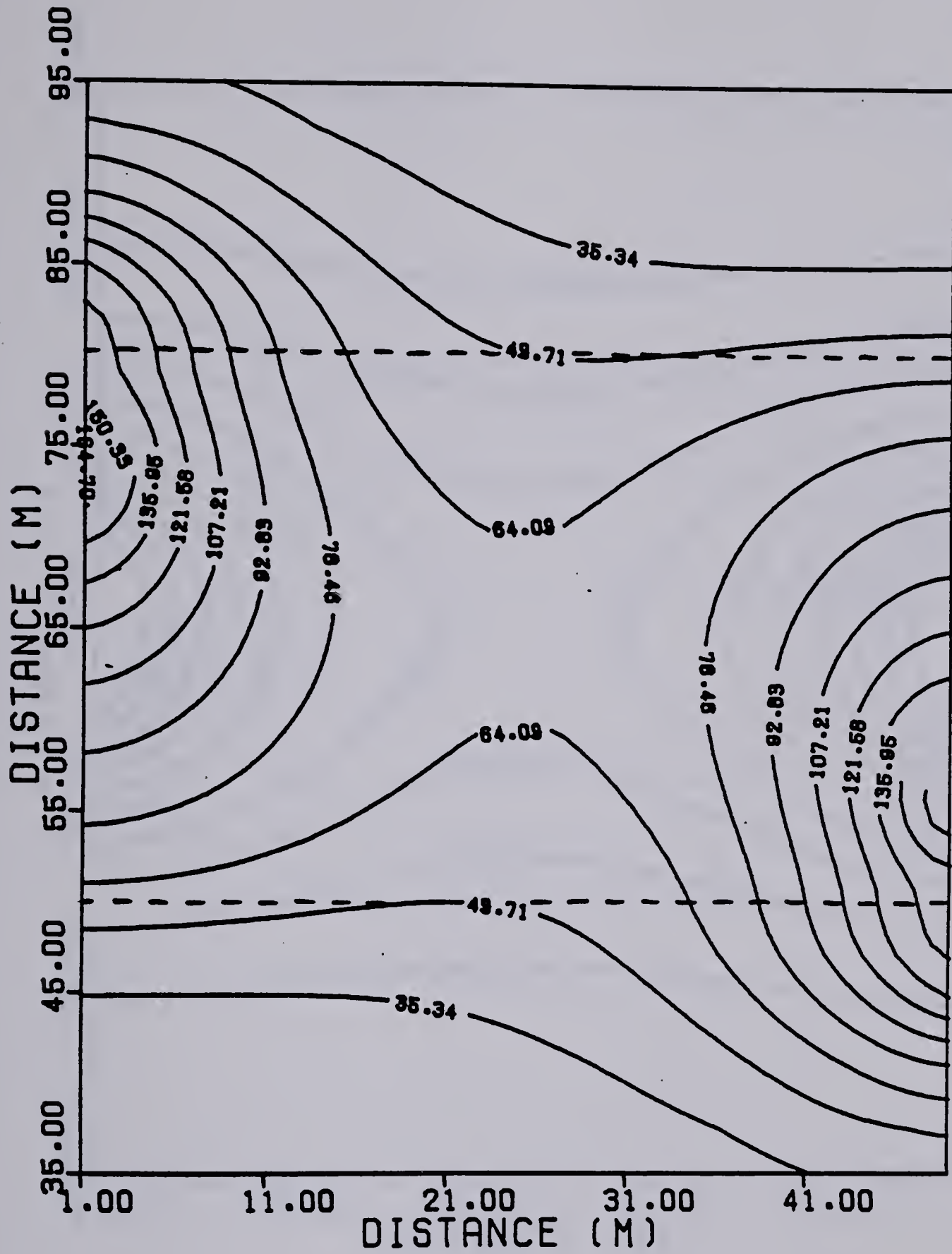


Figure 4.7 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 20, configuration B, with an electrical conductivity ratio (overburden, underburden/oil sand) of 5.

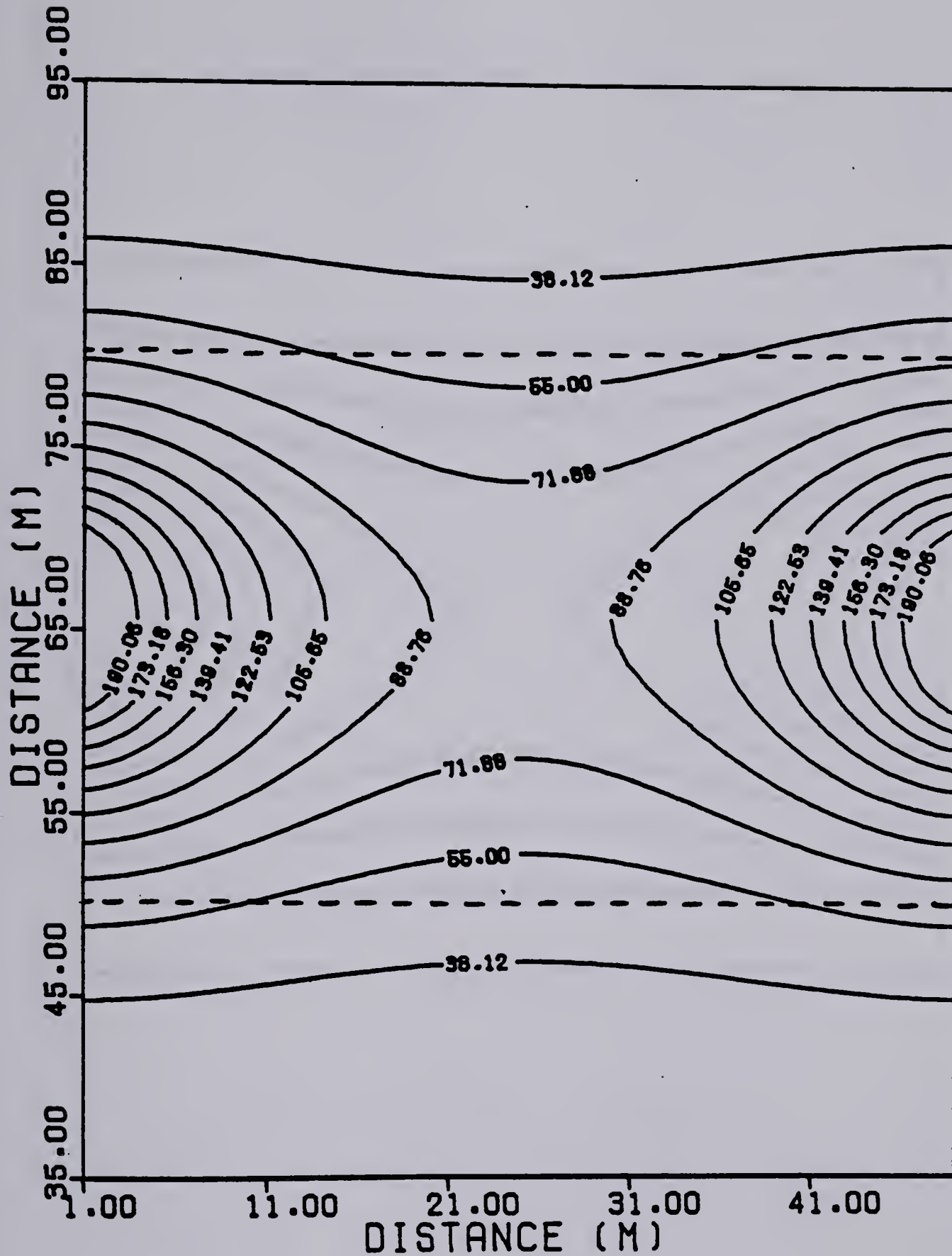


Figure 4.8 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 21, configuration A, with an electrical conductivity ratio (overburden, underburden/oil sand) of 1.

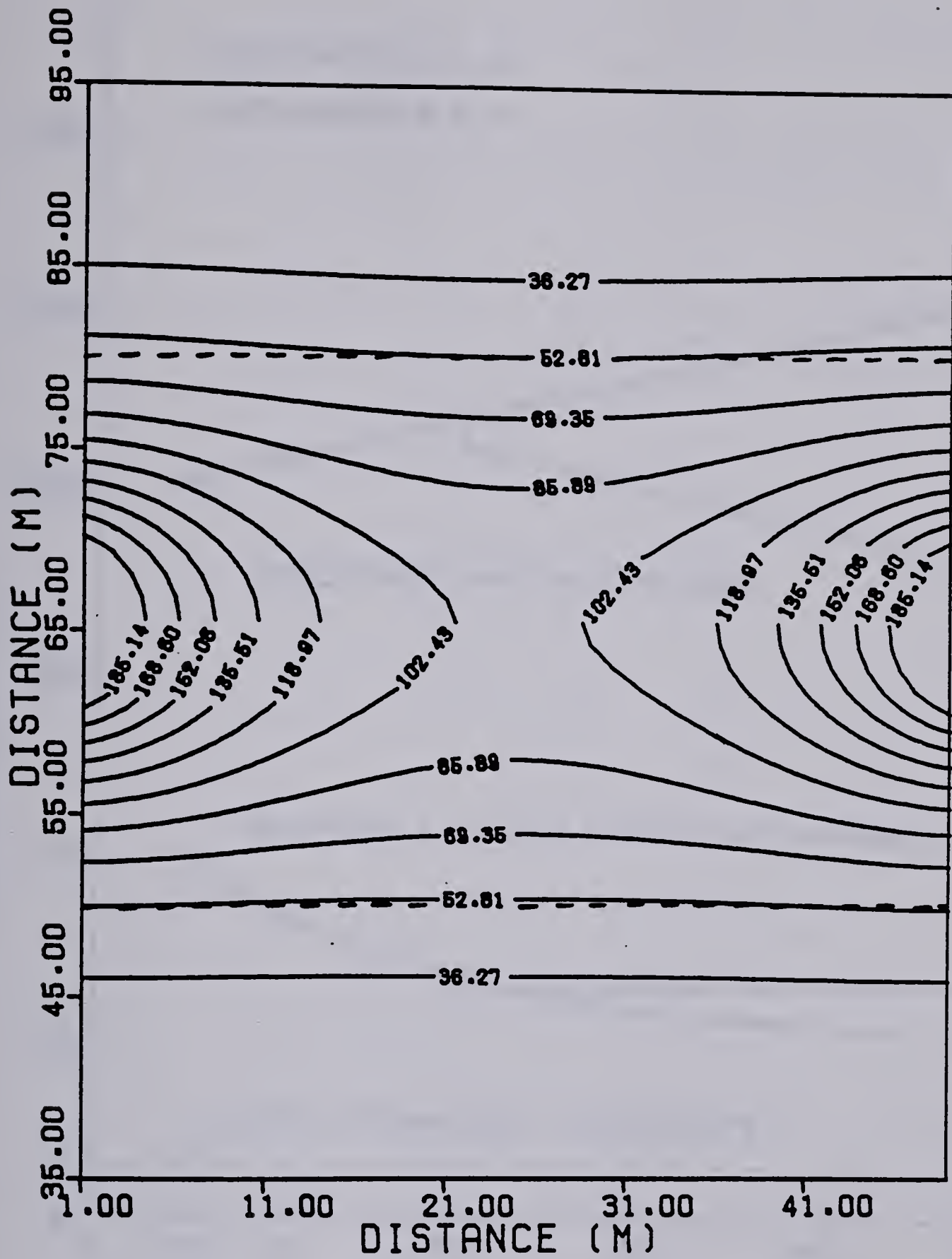


Figure 4.9 Contour plot of temperature in Celsius after one year of heating at 8 kW/m. Run no. 22, configuration A, with an electrical conductivity ratio (overburden, underburden/oil sand) of .5

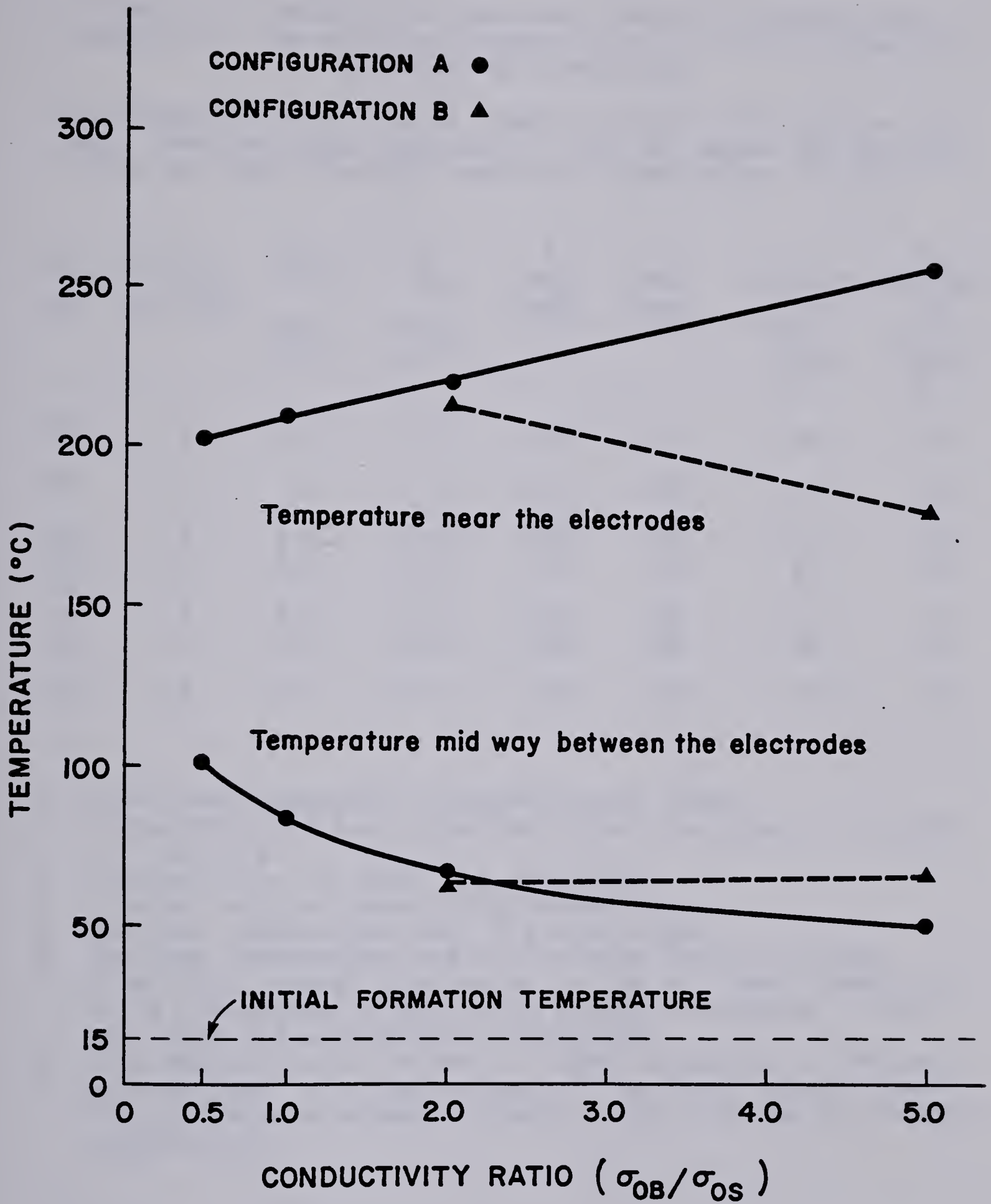


Figure 4.10 Temperature vs. the ratio of the electrical conductivities of the surrounding formations to that of the oil sand.

Table 4.1 Temperature rise and thermal efficiency as a function of the relative conductivity of the oil sand and surrounding formations.

The conductivity of the oil sand is 1.0×10^{-3} S/m for all runs. Constant power heating of 8 kW per meter was applied for one year. Initial reservoir temperature is 15°C .

1. Run No.	2. Config- uration	3. σ_{os} S/m $\times 10^{-3}$	4. σ_{us} S/m $\times 10^{-3}$	5. Max. Temp. $^{\circ}\text{C}$	6. Mid Temp. $^{\circ}\text{C}$	7. Heating in Oil Sand %	8. Energy in Oil Sand %
22	A	0.5	0.5	202	101	88	81
21	A	1.0	1.0	210	85	84	78
18	A	2.0	2.0	220	67	81	75
12	B	2.0	2.0	212	65	65	62
19	A	5.0	5.0	257	50	84	75
20	B	5.0	5.0	180	66	68	65
10	B	10.	10.	177	75	74	69

1. Runs were numbered in chronological order.
2. Dimensions and electrode positions are given in figures 4.1 and 4.2.
3. Conductivity of overlying formation.
4. Conductivity of underlying formation.
5. Maximum temperature near the electrodes.
6. Maximum temperature mid way between the electrodes.
7. Electrical energy dissipated in the oil sand formation as a percentage of the total energy dissipated in the oil sand and surrounding formations.
8. The energy stored in the oil sand formation at the end of one year, as a percentage of the total energy input. The difference between columns 7 and 8 is due to thermal conduction.

eighty percent of the energy in the oil sand after heating for one year. When the conductivity ratio is increased to five, configuration A will retain three quarters of the energy in the oil sand formation, while heating with configuration B will result in only sixty five percent of the energy input remaining in the oil sand at the end of the year. In both configurations most of the energy is lost by current passing through (and thus heating) the overlying and underlying formations. Thermal conduction typically accounts for the loss of five to ten percent of the total energy input, or ten to forty percent of the total energy lost to the surrounding formations.

When heating in configuration A, the conductivity ratio determines what fraction of the current enters the surrounding formations. As the conductivity ratio increases more of the current travels most of the distance between the electrodes in the overlying or underlying formations, where relatively low resistance is encountered. As a result the bulk of the voltage drop and the heating is in the oil sand near the electrodes, where the current is travelling from the electrode almost directly into the surrounding formations. This leads to a higher electrode temperature and a lower temperature midway between the electrodes. When heating in configuration B, a high conductivity ratio results in the overlying and underlying formations acting like large extended electrodes. Most of the voltage drop is across the oil sand formation from the overlying formation

to the underlying formation. However, in configuration B most of the current must travel some of the distance between the electrodes through the surrounding formations and this results in a lower fraction of the total heating occurring in the oil sand formation. This explains why, for a conductivity ratio of five, configuration B has a more uniform temperature profile in the oil sand, while configuration A has more of the energy input retained in the oil sand.

The total oil sand volume in both configurations A and B, per meter thick slice of the formation, is 1500 m^3 . The chemical energy content of oil sand is of the order of $10^{10} \text{ Joules/m}^3$, so the total chemical energy in the heated formation is about 10^{13} Joules . An electrical preheat of 8 kW/m for one year uses about $2.5 \times 10^{11} \text{ Joules}$ of electrical energy, which is of the order of one percent of the chemical energy in place.

4.2 Effects of changing the distance between the electrodes

Computer runs were carried out with 75 m and 100 m spacings between the electrodes, with the other dimensions and electrode positions as in configuration A (figure 4.1). The power input was increased to 12 kW/m for the 75 m spacing and to 16 kW/m for the 100 m spacing, but the heating time remained at one year. The results of these runs, and similar runs done with 50 m spacings, are given in table 4.2. The temperature contour plots for the end of the

year of heating are given in figures 4.11 to 4.17.

Even though the power output from the electrodes is increased in proportion to the distance between the electrodes, the maximum temperature near the electrodes remained constant for conductivity ratios of one half and one. For the runs with different electrical conductivities for the overlying and underlying formations, the maximum temperature near the electrodes increased by fifteen percent when the distance between the electrodes was increased from 50 m to 100 m. The temperature midway between the electrodes decreased with an increase in the distance between the electrodes. A graph of the temperature midway between the electrodes vs. the distance between the electrodes is given in figure 4.18. The fraction of the total energy input that is retained in the oil sand formation at the end of the year also declines with an increase in the distance between the electrodes.

As the distance between the electrodes increases, more of the current reaches the surrounding formations, and less desirable temperature profiles and thermal efficiencies result. A tradeoff must be made between the cost of the extra electrodes for a closely spaced heating configuration and the extra electrical energy and heating time required to obtain the same temperature profile for a larger spacing. The effect of changing the distance between the electrodes is more pronounced for higher conductivity ratios. The optimal distance between the electrodes will be a function

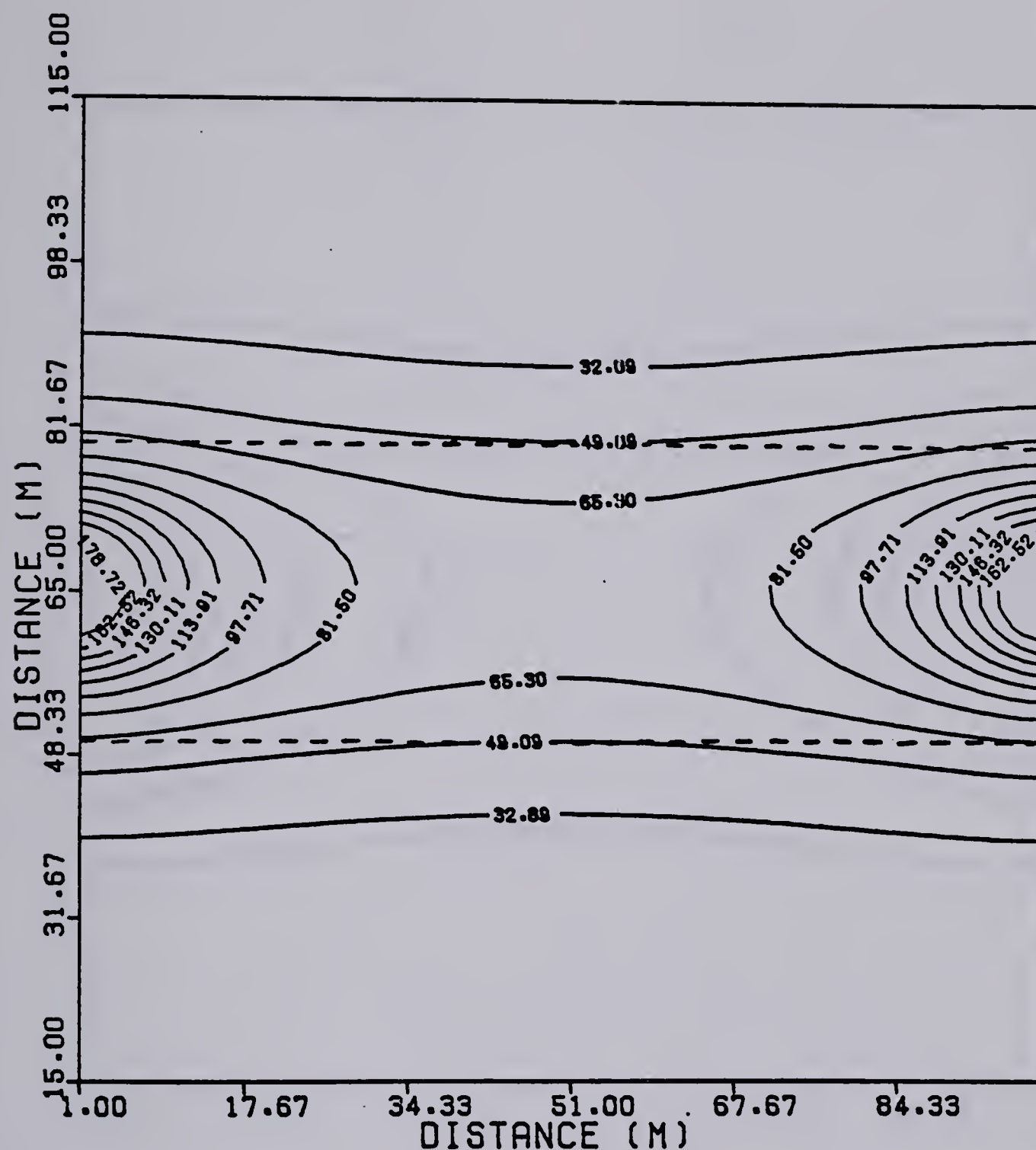


Figure 4.11 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 23, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of .5

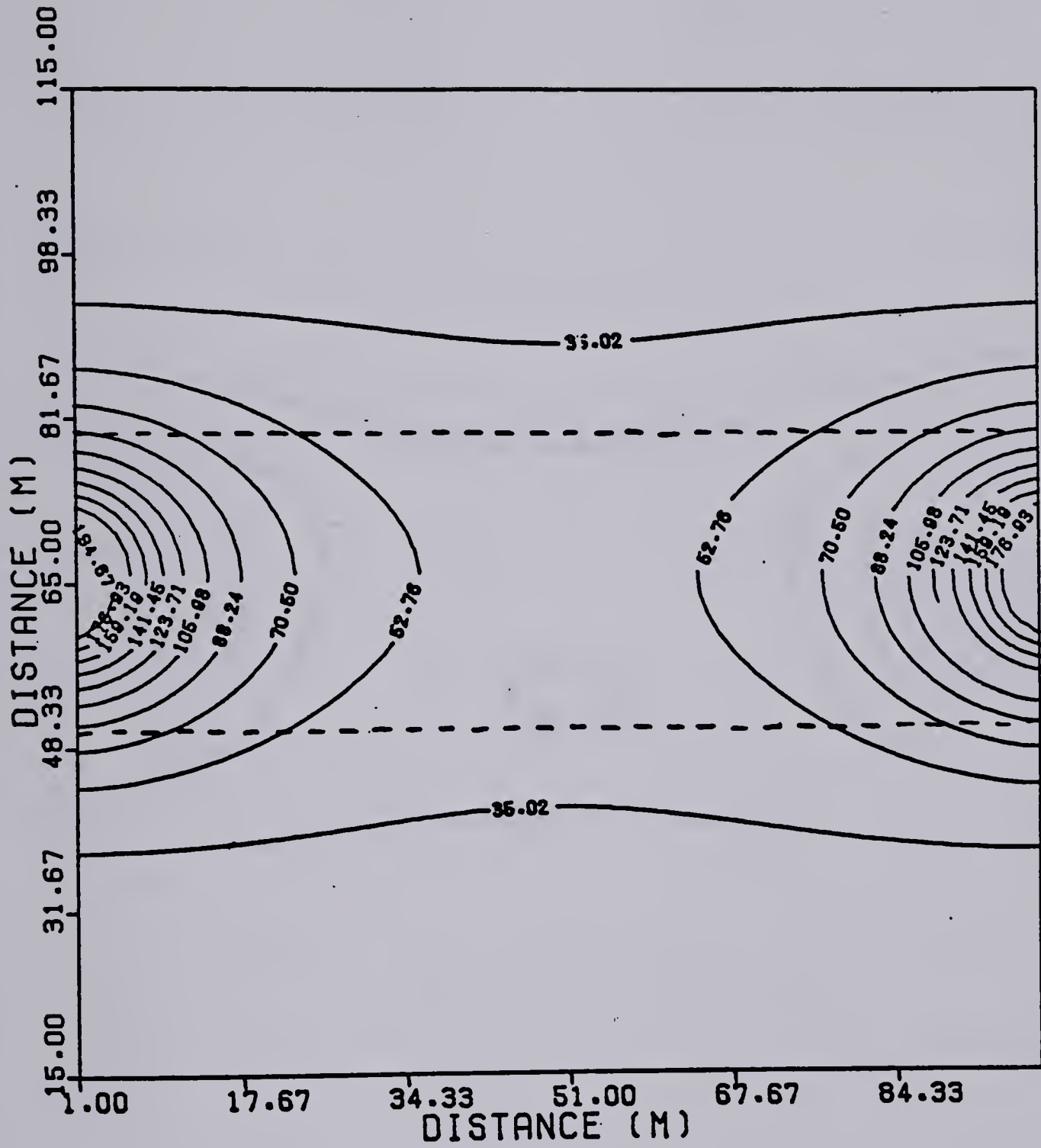


Figure 4.12 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 24, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of 1.

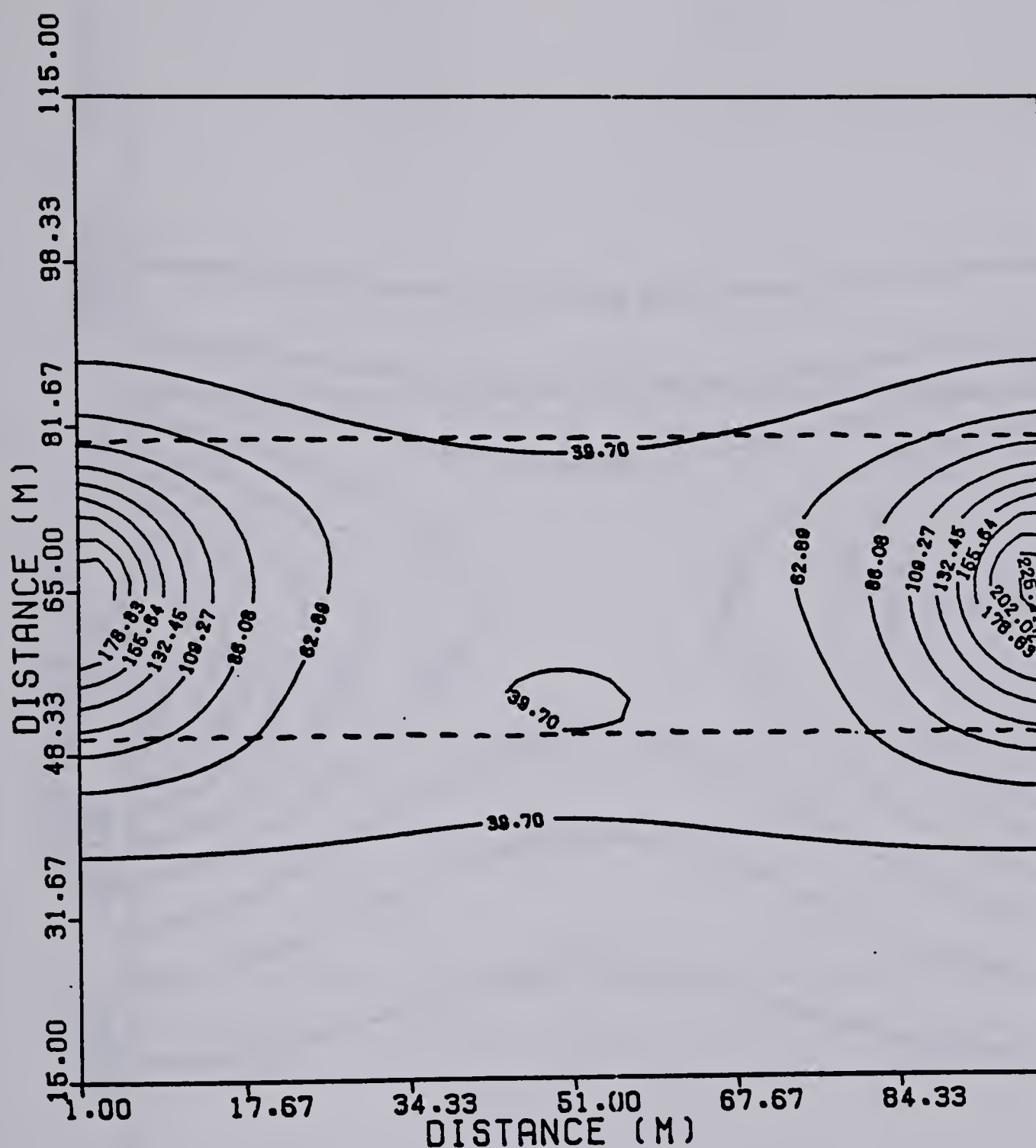


Figure 4.13 Contour plot of temperature in Celsius at the end of heating for one year at 16 kW/m. Run no. 25, overburden half as conductive and underburden twice as conductive as oil sand.

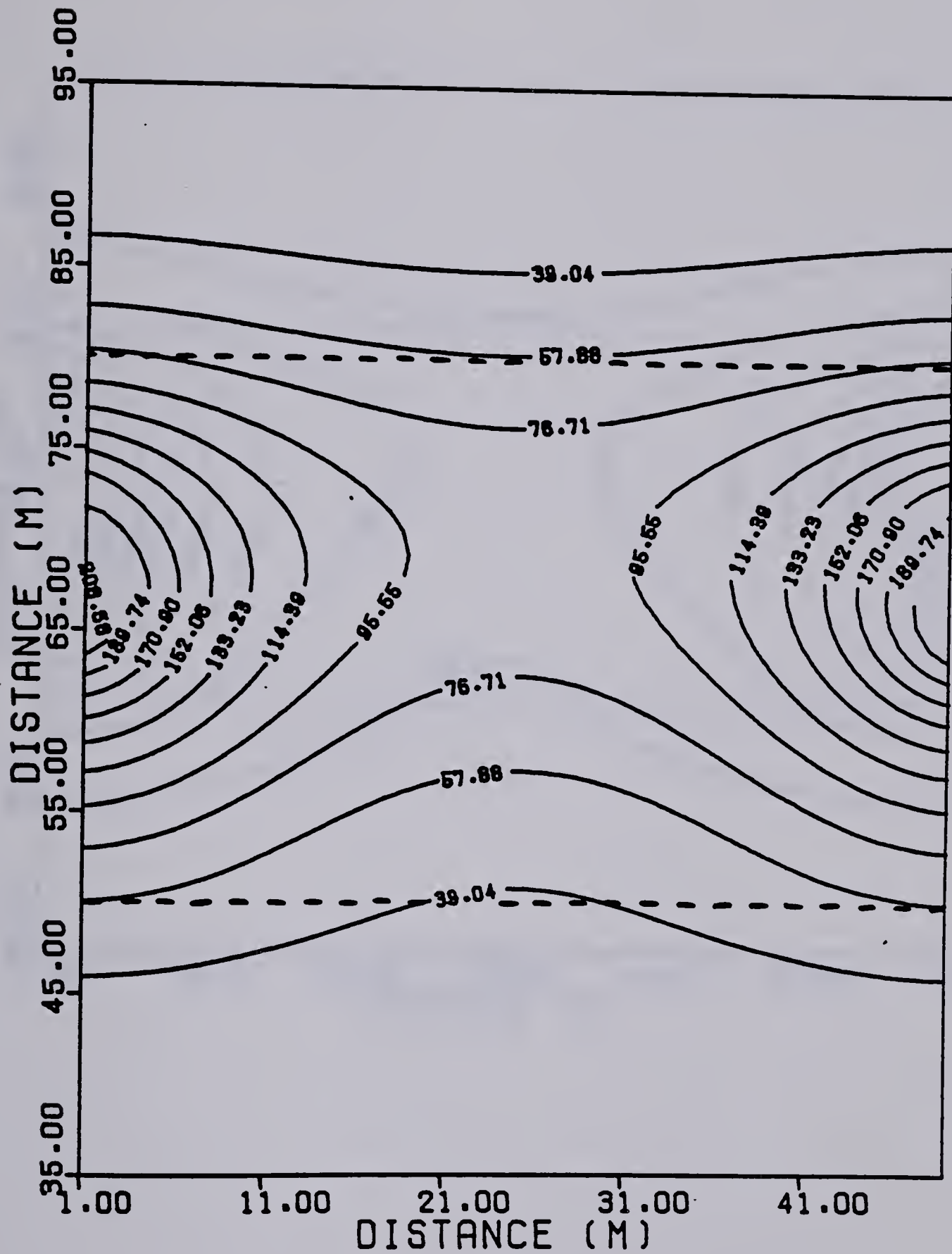


Figure 4.14 Contour plot of temperature in Celsius at the end of heating for one year at 8 kW/m. Run no. 26, overburden half as conductive and underburden twice as conductive as oil sand.

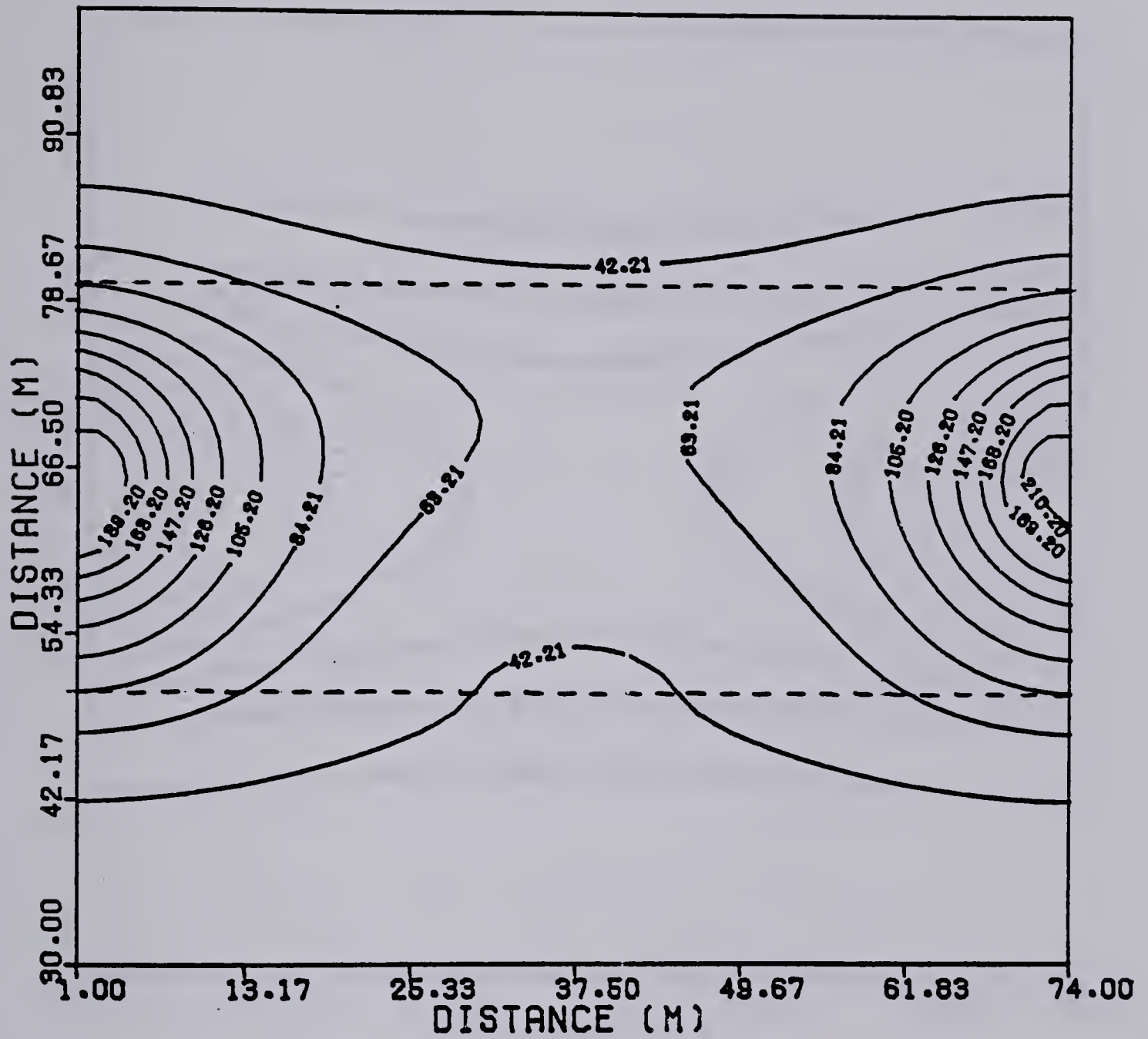


Figure 4.15 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 32, overburden half as conductive and underburden twice as conductive as oil sand.

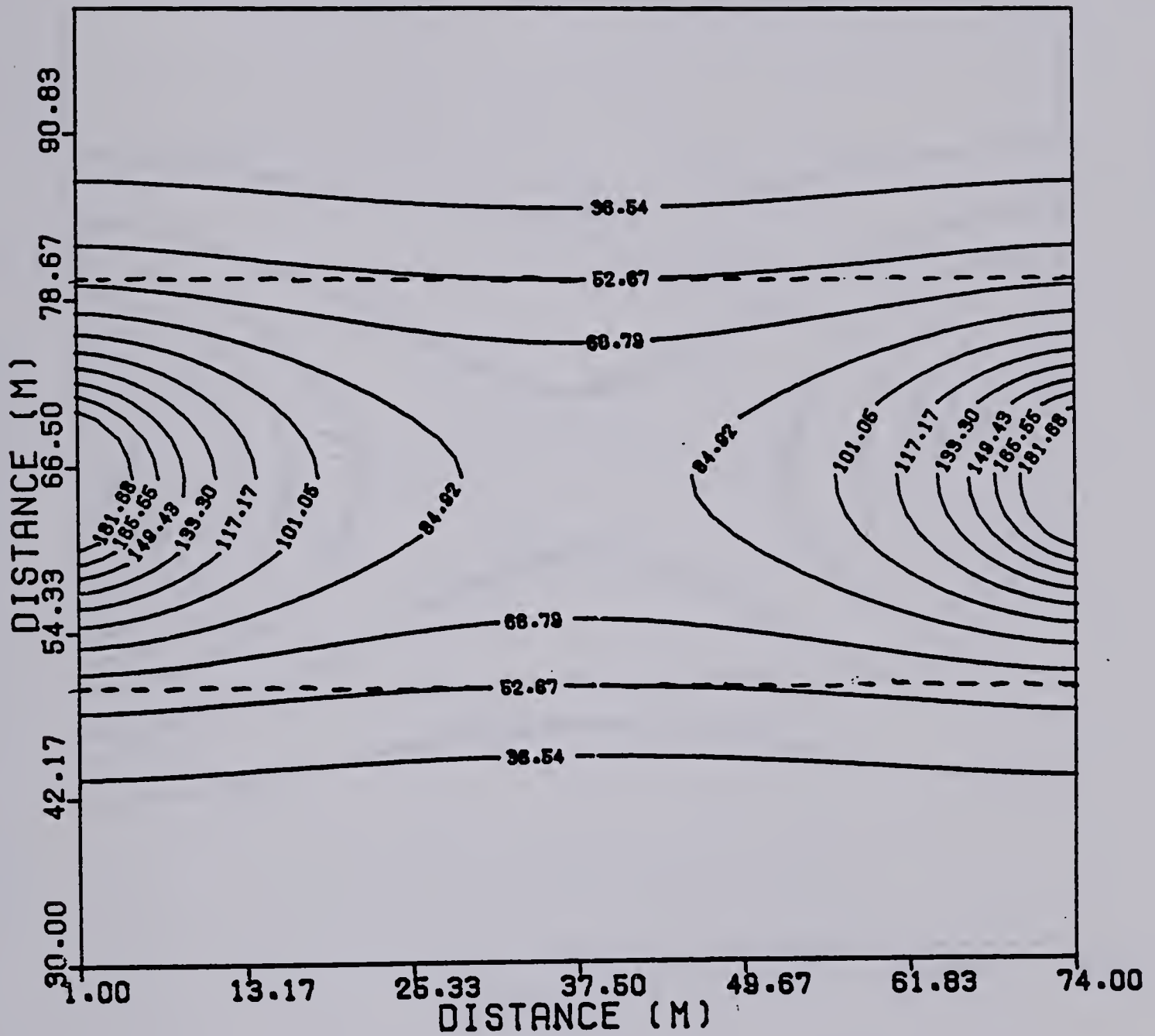


Figure 4.16 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 34, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of .5

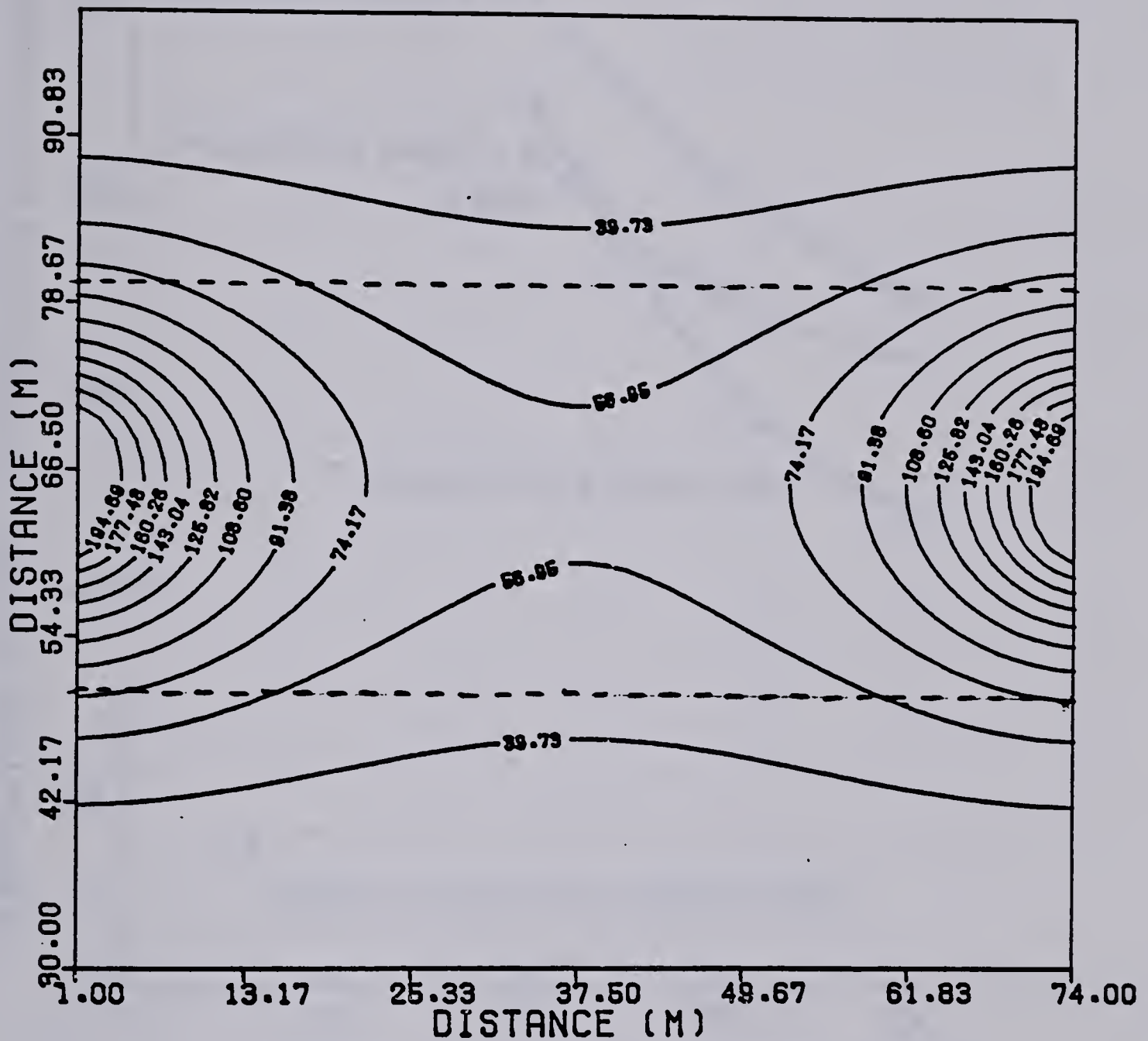
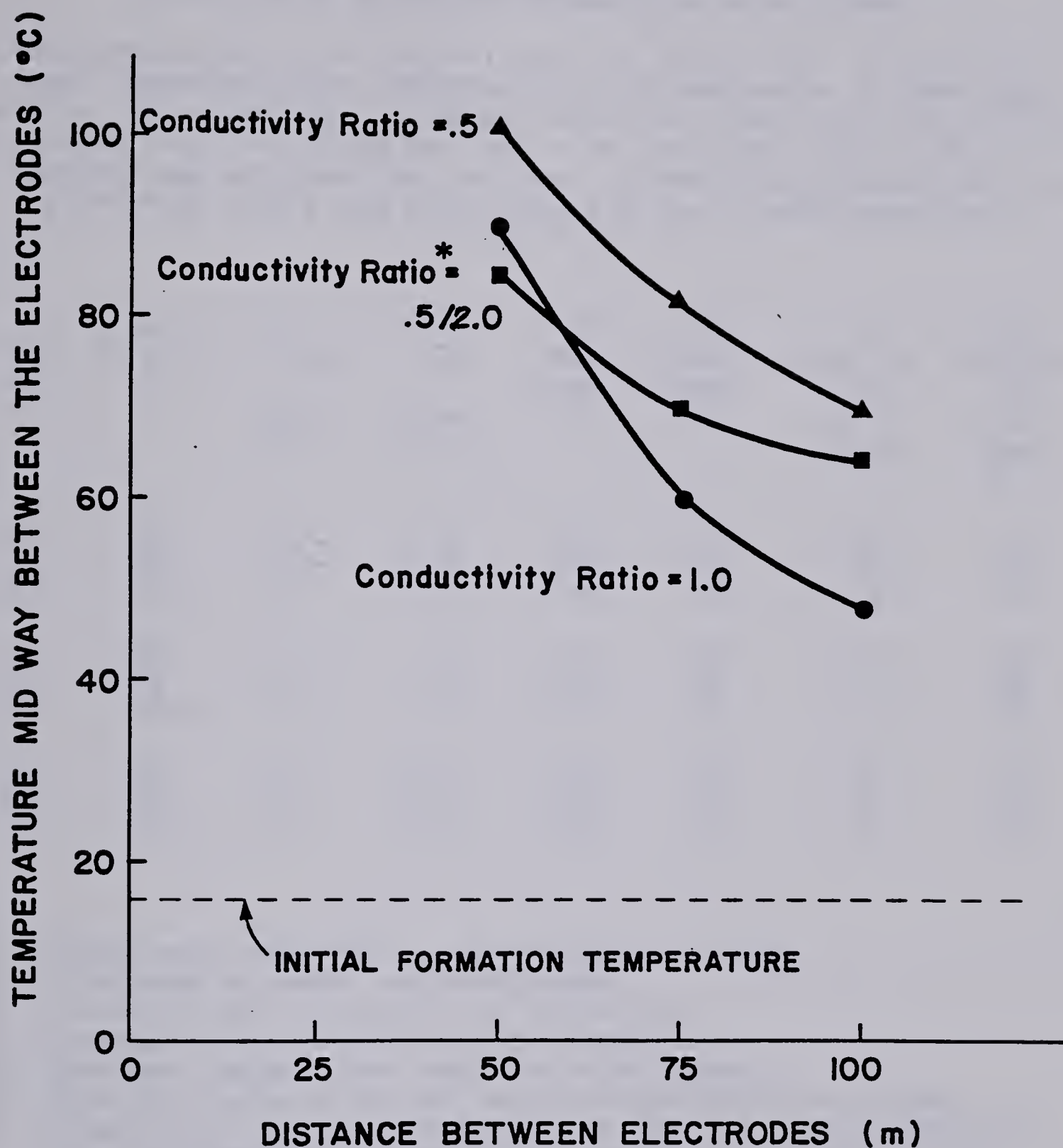


Figure 4.17 Contour plot of temperature in Celsius at the end of heating for one year at 12 kW/m. Run no. 35, configuration A, with a conductivity ratio (overburden, underburden/ oil sand) of 1.



* Overlying formation is half as conductive as the oil sand and the underlying formation is twice as conductive as the oil sand.

Figure 4.18 Temperature midway between the electrodes vs. the distance between the electrodes. Electrode positions are as in configuration A, except for the mixed conductivity ratio where the electrodes were moved up three meters.

Table 4.2 Temperature rise and thermal efficiency as a function of distance between the electrodes.

The conductivity of the oil sand is 1.0×10^{-3} S/m for all runs. Constant power heating of 8 kW per meter in the runs with a 50 m spacing, 12 kW per meter in the runs with a 75 m spacing, and 16 kW per meter in the runs with a 100 m spacing was applied for one year. Formation thicknesses and electrode sizes and positions are as in configuration A (Fig. 4.1).

1. Run No.	2. Spacing m	3. σ_{OB} S/m $\times 10^{-3}$	4. σ_{UB} S/m $\times 10^{-3}$	5. Max. Temp. °C	6. Mid Temp. °C	7. Heating in Oil Sand %	8. Energy in Oil Sand %
22	50	0.5	0.5	202	101	88	81
34	75	0.5	0.5	196	82	79	73
23	100	0.5	0.5	195	72	72	67
21	50	1.0	1.0	210	85	84	78
35	75	1.0	1.0	210	60	71	66
24	100	1.0	1.0	210	48	62	58
26	50	0.5	2.0	230	90	85	79
32	75	0.5	2.0	258	74	74	68
25	100	0.5	2.0	264	46	65	60

1. Runs were numbered in chronological order.
2. Distance between the electrodes.
3. Conductivity of overlying formation.
4. Conductivity of underlying formation.
5. Maximum temperature near the electrodes.
6. Maximum temperature mid way between the electrodes.
7. Electrical energy dissipated in the oil sand formation as a percentage of the total energy dissipated in the oil sand and surrounding formations.
8. The energy stored in the oil sand formation at the end of one year, as a percentage of the total energy input. The difference between columns 7 and 8 is due to thermal conduction.

of many parameters, with two important factors being the cost of the wells and electrodes and the relative conductivities of the surrounding formations to the oil sand.

5. Conclusions

The results of the full scale simulation runs done using the computer program MEGAERA are encouraging. These results indicate that, by using less than five percent of the chemical energy in place in a typical thickness Athabasca oil sand formation, it is possible to raise the temperature midway between the electrodes to 80°C , with higher temperatures near the electrodes. The viscosity of the bitumen (Athabasca oil sand) would be about 1000 cp midway between the electrodes, and considerably less near the electrodes. This is low enough to allow an efficient steam drive to be conducted.

The comparisons done between the analytic solution and the computer simulation indicate that the finite difference scheme used was correct. The convergence error due to the explicit coupling of the electrical and thermal equations remains, but, if the maximum temperature change per timestep is kept less than five percent, this error will not be significant.

The best test of both the mathematical model and the finite difference scheme that were used is conducted by comparing the simulator results with a physical model run. When this was done the simulator results were in agreement with the measured temperatures from the physical model run, except in the immediate vicinity of the electrodes. Thus, at least for temperatures up to 90°C (above which accurate electrical conductivity data is not available), the

mathematical model used will accurately predict temperatures and resistance for electrical heating of solid materials.

There are several items which should be kept in mind when interpreting the results of the full scale simulator runs. First, the electrical and thermal properties of oil sand have not been reported in the literature for temperatures above 90°C. In the simulator the thermal properties were assumed independent of temperature, and the electrical conductivity was assumed to increase linearly with temperature, up to 250°C. Second, the conductivity of the oil sand near the electrodes in a field test would be altered by the injection of brine near the electrode. These two factors may result in significant error in the predicted temperatures near the electrodes. Finally, the conductivity of the oil sand was made uniform throughout the formation for the simulation runs. This was by choice and not due to any limitation of the simulator. In an actual oil sand formation there is probably variations in electrical conductivity with height in the formation and due to the presence of shale breaks and clay deposits.

The investigation to date indicates that the electrical preheat method may be developed into an economical method of preparing an oil sand formation for a steam flood or fire flood. Further measurement of the electrical and thermal properties of oil sand need to be performed at formation pressures and temperatures in the range of 100°C to 300°C. The computer simulator should be extended to three

dimensions so that simulation of five spot patterns are possible in addition to the parallel plate electrode (or line drive) geometry which was studied in this thesis. Finally, due to variations in the conductivities of the oil sand and the surrounding formations no one electrode configuration is optimal and each recovery location will have to be investigated individually to determine the optimal electrode size, positioning and spacing.

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61	C	ELEPOT	CALCULATE THE ELECTRICAL POTENTIAL	2.2
62	C	ELECOF	CALCULATE COEFFICIENTS OF DIFFERENCE EQUATION	2.3
63	C	THOMAS	SOLVE TRIDIAGONAL SYSTEM BY THOMAS ALGORITHM	2.4
64	C	MAXDIF	FIND THE MAXIMUM DIFFERENCE BETWEEN TEM3, TEM1	2.5
65	C	ECOND	CALCULATE THE ELECTRICAL CONDUCTIVITY	2.6
66	C	QCALC	CALCULATE THE HEATING RATES FOR THE GRID	2.7
67	C	TCALC	SOLVE THE HEAT DIFFUSION EQUATION	2.8
68	C	ENGBAL	CALCULATE THE ENERGY BALANCE FOR THE TIMESTEP	2.9
69	C	ELECUR	CALCULATE THE CURRENT THROUGH A SURFACE	2.10
70	C			
71	C		OUTPUT.	CLASS 3
72	C			
73	C	OUTPUT(1)	CONTROL THE OUTPUT	3.1
74	C	OUTGRD(1)	OUTPUT ONE OF THE GLOBAL VARIABLE ARRAYS	3.2
75	C	ALINTP(7)	DO A LINEAR INTERPOLATION	3.3
76	C	OUTINT(2)	INTERPOLATE AND PRINT A GLOBAL VARIABLE	3.4
77	C	OUTR	OUTPUT A LABEL AND A REAL VARIABLE	3.5
78	C	OUTI	OUTPUT A LABEL AND AN INTEGER VARIABLE	3.6
79	C	OUTH	OUTPUT A LABEL AND A HOLLERITH VARIABLE	3.7
80	C	OUTTAP(1)	OUTPUT RUN INFORMATION TO MAGNETIC TAPE	3.8
81	C			
82	C		EPILOGUE.	CLASS 4
83	C			
84	C	TESEND	TEST FOR COMPLETION OF RUN	4.1
85	C	ENDRUN	TERMINATE THE RUN	4.2
86	C			
87	C		DIAGNOSTICS.	CLASS 5
88	C			
89	C	REPORT(3)	CONTROL THE DIAGNOSTICS	5.1
90	C	CLIST(2)	PRINT COMMON VARIABLES	5.2
91	C	ARRAYS(2)	PRINT COMMON ARRAYS	5.3
92	C			
93	C		UTILITIES.	CLASS U
94	C			
95	C	MESSAGE(1)	PRINT 48-CHARACTER MESSAGE ON OUTPUT CHANNEL	U.1
96	C	PAGE	FETCH NEW PAGE ON OUTPUT CHANNEL	U.2
97	C	BLINES(1)	INSERT BLANK LINES ON OUTPUT CHANNEL	U.3
98	C	RVAR(2)	PRINT NAME AND VALUE OF REAL VARIABLE	U.4
99	C	IVAR(2)	PRINT NAME AND VALUE OF INTEGER VARIABLE	U.5
100	C	HVAR(2)	PRINT NAME AND VALUE OF HOLLERITH VARIABLE	U.6
101	C	LVAR(2)	PRINT NAME AND VALUE OF LOGICAL VARIABLE	U.7
102	C	RARRAY(3)	PRINT NAME AND VALUES OF REAL ARRAY	U.8
103	C	IARRAY(3)	PRINT NAME AND VALUES OF INTEGER ARRAY	U.9
104	C	HARRAY(3)	PRINT NAME AND VALUES OF HOLLERITH ARRAY	U.10
105	C	REPTH(3)	PRINT HEADING FOR DIAGNOSTIC REPORT	U.11
106	C	RUNTIM	UPDATE CPU TIME AND PRINT IT	U.12
107	C	DAYTIM	PRINT DATE AND TIME	U.13
108	C	RESETR(3)	RESET REAL ARRAY TO SPECIFIED VALUE	U.14
109	C	RESETI(3)	RESET INTEGER ARRAY TO SPECIFIED VALUE	U.15
110	C	RESETH(3)	RESET HOLLERITH ARRAY TO SPECIFIED VALUE	U.16
111	C	JOBTIM	FETCH ALLOCATED JOBTIME	U.17
112	C	LARRAY(3)	PRINT NAME AND VALUES OF LOGICAL ARRAY	U.18
113	C	RESETL(3)	RESET LOGICAL ARRAY TO SPECIFIED VALUE	U.19
114	C	RARRAY2	PRINT DOUBLY-SUBSCRIPTED ARRAY	U.20
115	C	SCALER(3)	SCALE A REAL ARRAY BY A REAL VALUE	U.21
116	C	SCALEI(3)	SCALE AN INTEGER ARRAY BY AN INTEGER VALUE	U.22
117	C	COPYR(5)	COPY ONE REAL MATRIX INTO ANOTHER	U.23
118	C	COPYI(5)	COPY ONE INTEGER MATRIX INTO ANOTHER	U.24
119	C	SIGNR(2)	CHANGE THE SIGN OF A REAL MATRIX	U.25
120	C	SIGNI(2)	CHANGE THE SIGN OF AN INTEGER MATRIX	U.26


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121 C DUMCOM(3) DUMP SELECTED COMMON BLOCKS U.27
122 C
123 C
124 CL C1.1. BASIC SYSTEM PARAMETERS
125 C VERSION 2B 14.8.73 KVR/MHH CULHAM
126 C COMMON/COMBAS/
127 C
128 C
129 C ALTIME TIME ALLOCATED TO JOB, (MINS) R 1.1
130 C CPTIME CPU TIME USED SO FAR ON THIS JOB, (MINS) R 1.1
131 C LABEL1(12) LABEL DESCRIBING THE RUN IA 1.1
132 C LABEL2(12) LABEL DESCRIBING THE RUN IA 1.1
133 C LABEL3(12) LABEL DESCRIBING THE RUN IA 1.1
134 C LABEL4(12) LABEL DESCRIBING THE RUN IA 1.1
135 C LABEL5(12) LABEL AVAILABLE TO PROGRAMMER IA 1.1
136 C LABEL6(12) LABEL AVAILABLE TO PROGRAMMER IA 1.1
137 C LABEL7(12) LABEL RESERVED FOR SYSTEM USE IA 1.1
138 C LABEL8(12) LABEL RESERVED FOR SYSTEM USE IA 1.1
139 C NOIARY CHANNEL FOR DIARY I 1.1
140 C NIN CURRENT INPUT CHANNEL I 1.1
141 C NLEDGE CHANNEL FOR RESTART RECORDS I 1.1
142 C NLENO .TRUE. IF RUN TO BE TERMINATED L 1.1
143 C NLRES .TRUE. IF RUN TO BE RESTARTED L 1.1
144 C NONLIN CHANNEL FOR ONLINE INPUT-OUTPUT I 1.1
145 C NOUT CURRENT OUTPUT CHANNEL I 1.1
146 C NPRINT CHANNEL FOR PRINTED OUTPUT I 1.1
147 C NPUNCH CHANNEL FOR CARO OUTPUT (OR EQUIVALENT) I 1.1
148 C NREAD CHANNEL FOR CARO INPUT I 1.1
149 C NREC CURRENT RECORD NUMBER I 1.1
150 C NRESUM RESUME FROM RECORD ON THIS CHANNEL I 1.1
151 C NRUN MAXIMUM NUMBER OF STEPS I 1.1
152 C NSTEP CURRENT STEP NUMBER I 1.1
153 C STIME START TIME, (MINS) R 1.1
154 C
155 C
156 C-----
157 C
158 C
159 CL C1.9. DEVELOPMENT AND DIAGNOSTIC PARAMETERS
160 C VERSION 1B 14.8.73 KVR/MHH CULHAM
161 C COMMON/COMDOP/
162 C
163 C
164 C
165 C MAXOUM MAXIMUM DIMENSION OF DUMP ARRAYS I 1.9
166 C MXOUMP ACTUAL DIMENSION OF DUMP ARRAYS I 1.9
167 C NAOUMP(M) CODES FOR ARRAY DUMPS IA 1.9
168 C NCLASS MOST RECENT CLASS REPORTED I 1.9
169 C NLCEO .TRUE. IF CLASS 0 REPORT HEADS REQUIRED L 1.9
170 C NLHEAO(9) .TRUE. IF CLASSES 1-9 REPORT HEADS REQUIRED LA 1.9
171 C NLOMT1(50) CLASS 1 SUBPROGRAM SELECTOR LA 1.9
172 C NLOMT2(50) CLASS 2 SUBPROGRAM SELECTOR LA 1.9
173 C NLOMT3(50) CLASS 3 SUBPROGRAM SELECTOR LA 1.9
174 C NLREPT .TRUE. IF ANY REPORT REQUIRED L 1.9
175 C NPOUMP(M) CODES FOR DUMPING POINTS IA 1.9
176 C NPOINT MOST RECENT POINT REPORTED I 1.9
177 C NSUB MOST RECENT SUBPROGRAM REPORTED I 1.9
178 C NVOUMP(M) CODES FOR DUMPING VARIABLES IA 1.9
179 C
180 C-----

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181 C
182 C      1.2      /COMGLO/ - GLOBAL VARIABLES
183 C
184 C  DELTAX      WIDTHS OF GRID BLOCKS                      R  1.2
185 C  DELTAY      HEIGHT OF GRID BLOCKS                      R  1.2
186 C  DTIME       LENGTH OF TIMESTEP ( DELTA TIME)          R  1.2
187 C  ELECON       ELECTRICAL CONDUCTIVITY                  R  1.2
188 C  ELEGEO       ELECTRICAL GEOMETRY                      R  1.2
189 C              NEGATIVE - DOMAIN POINT
190 C              ZERO      - NOT IN DOMAIN
191 C              POSITIVE - ELECTRODE
192 C  QTHERM       HEAT GENERATED BY ELECTRIC FIELD        R  1.2
193 C  POTENT       ELECTRICAL POTENTIAL                    R  1.2
194 C  TEMP         TEMPERATURE                             R  1.2
195 C  THICK        THICKNESS OF TWO DIMENSIONAL SLICE      R  1.2
196 C  THMGEO       THERMAL GEOMETRY                        R  1.2
197 C  TIME         CURRENT VALUE OF THE TIME                R  1.2
198 C  XCOORD       X COORDINATES OF GRIDPOINTS             R  1.2
199 C  YCOORD       Y COORDINATES OF GRIDPOINTS             R  1.2
200 C              ORIGIN AT LOWER LEFT CORNER OF (1,1) BLOCK
201 C  XMIN         MINIMUM X FOR INTERPOLATED PRINTOUT     R  1.2
202 C  XMAX         MAXIMUM X FOR INTERPOLATED PRINTOUT     R  1.2
203 C  YMIN         MINIMUM Y FOR INTERPOLATED PRINTOUT     R  1.2
204 C  YMAX         MAXIMUM Y FOR INTERPOLATED PRINTOUT     R  1.2
205 C
206 C -----
207 C
208 C      1.3      /COMELE/ - ELECTRICAL COEFFICIENTS
209 C
210 C  ECXM         COEFFICIENT OF FINITE DIFFERENCE EQU.    R  1.3
211 C  EEXP         COEFFICIENT IN POSITIVE X DIRECTION      R  1.3
212 C  ECPM         " " NEGATIVE Y " "                    R  1.3
213 C  ECPY         " " POSITIVE Y DIRECTION                R  1.3
214 C  EXMP         SUM OF THE TWO X DIRECTION COEFFICIENTS R  1.3
215 C  EYMP         SUM OF THE TWO Y DIRECTION COEFFICIENTS R  1.3
216 C  ERHS         RIGHT HAND SIDE OF DIFFERENCE EQU.      R  1.3
217 C  ELEVOL       VOLTAGES OF DIFFERENT ELECTRODES        R  1.3
218 C  ELEALP       COEFFICIENTS FOR CONDUCTIVITY CALC.     R  1.3
219 C  ELEBET       " " " " " " " " " " " " " " " " " " " " R  1.3
220 C  ELEPAR       ITERATION PARAMETERS FOR A.O.I.P.       R  1.3
221 C  EPSELE       CONVERGENCE CRITERIA FOR POTENTIAL      R  1.3
222 C
223 C -----
224 C
225 C      1.4      /COMTHM/ - THERMAL CONDUCTIVITY AND CAPACITY
226 C
227 C  THMCON       THERMAL CONDUCTIVITIES                    R  1.4
228 C  THMCP        VOLUMETRIC HEAT CAPACITY                R  1.4
229 C  THMTEM       VECTOR OF CONSTANT TEMPERATURES         R  1.4
230 C  TCYP         COEFFICIENT OF THE THERMAL EQU. ( Y POS. ) R  1.4
231 C  TCXP         " " " " " " " " " " " " " " " " " " " " ( X POS. ) R  1.4
232 C  TCXM         " " " " " " " " " " " " " " " " " " " " ( X NEG. ) R  1.4
233 C  TCYM         " " " " " " " " " " " " " " " " " " " " ( Y NEG. ) R  1.4
234 C  TCX          SUM OF X COEFFICIENTS                    R  1.4
235 C  TCY          SUM OF Y COEFFICIENTS                    R  1.4
236 C  TCRHS       TERMS ON CONSTANT TEMPERATURE BOUNDARY  R  1.4
237 C
238 C -----
239 C
240 C      1.5      /COMTEM/ - TEMPORARY ARRAYS

```


241	C			
242	C	TEM1	TWO DIMENSION ARRAY FOR A.O.I.	R 1.5
243	C	TEM2		R 1.5
244	C	TEM3		R 1.5
245	C	T1	ONE DIMENSION ARRAY FOR THOMAS ALGOR.	R 1.5
246	C	T2		R 1.5
247	C	T3		R 1.5
248	C	T4		R 1.5
249	C	T5		R 1.5
250	C			
251	C			
252	C			
253	C		1.6 /COMOIM/ - INTEGER COMMON BLOCK	
254	C			
255	C	NX	ACTUAL NUMBER OF GRID BLOCKS IN X DIR.	I 1.6
256	C	NY	ACTUAL NUMBER OF GRID BLOCKS IN Y DIR.	I 1.6
257	C	NOX	ACTUAL DIMENSION OF ARRAYS	I 1.6
258	C	NOY	ACTUAL DIMENSION OF ARRAYS	I 1.6
259	C	NEQU	NUMBER OF EQUATION FOR THOMAS ALGOR.	I 1.6
260	C	NALPHA	NUMBER OF ITERATION PARAMETERS USED	I 1.6
261	C	MITER	CURRENT ITERATION COUNTER FOR POTENTIAL	I 1.6
262	C	MMAX	MAXIMUM ALLOWED VALUE OF MITER	I 1.6
263	C	NREG	NUMBER OF DIFFERENT REGIONS IN PROBLEM	I 1.6
264	C	NGEO	0 IF IN VERTICAL MODE, 1 IN HORIZONTAL	I 1.6
265	C	NERROR	ERROR RETURN CODE FROM TIMESTEP ROUTINES	I 1.6
266	C	NTYPE	INDICATES TYPE OF HEATING	I 1.6
267	C		1- CONSTANT VOLTAGE	
268	C		2- CONSTANT CURRENT	
269	C		3- CONSTANT POWER	
270	C		4- NO HEATING	
271	C	NSPO	NUMBER OF TIME STEPS PER OUTPUT	I 1.6
272	C	NSTO	NUMBER OF TIMESTEPS BETWEEN TAPE STORES	I 1.6
273	C	NPX	NUMBER OF X INTERVALS FOR INTERPOLATION	I 1.6
274	C	NPY	NUMBER OF Y INTERVALS FOR INTERPOLATION	I 1.6
275	C	NIJ	INDICATES IF SURFACE OF CURRENT INTEGRAL	
276	C		IS PERPENDICULAR TO X OR Y	I 1.6
277	C	NCI	INDICE OF GRIDLINE WHICH INTEGRAL IS ALONG	I 1.6
278	C			
279	C			
280	C			
281	C		1.7 /COMCON/ - HEATING CONTROL VARIABLES	
282	C			
283	C	HTIME	TOTAL TIME OF HEATING	R 1.7
284	C	CTIME	TOTAL TIME OF COOLING	R 1.7
285	C	CCUR	CONSTANT VALUE OF CURRENT	R 1.7
286	C	CPOW	CONSTANT VALUE OF CURRENT	R 1.7
287	C	OTEMP	MAXIMUM RELATIVE CHANGE IN TEMPERATURE	R 1.7
288	C	DELT	ACTUAL CHANGE IN TEMPERATURE FOR TIMESTEP	R 1.7
289	C	CUR	CURRENT CALCULATED FROM CURRENT INTEGRAL	R 1.7
290	C	VOLTS	ACTUAL VOLTAGE ACROSS ELECTRODES	R 1.7
291	C	CVOL	VOLTAGE USED IN PROBLEM DEFINITION	R 1.7
292	C	RESIST	RESISTANCE BETWEEN ELECTRODES	R 1.7
293	C	POWER	ELECTRICAL POWER INPUT DURING TIMESTEP	R 1.7
294	C	TINIT	INITIAL TEMPERATURE OF THE FORMATION	R 1.7
295	C	OEENG	ELECTRICAL ENERGY INPUT FOR THE TIMESTEP	R 1.7
296	C	TEENG	TOTAL ELECTRICAL ENERGY INPUT FOR THE RUN	R 1.7
297	C	OQENG	HEAT PRODUCED FOR THE TIMESTEP	R 1.7
298	C	TQENG	TOTAL HEAT PRODUCED IN THE RUN	R 1.7
299	C	OENG	VECTOR OF HEATING IN EACH REGION	R 1.7
300	C	TTENG	ENERGY IN THE TEMPERATURE CHANGE	R 1.7


```

301      C  TENG          VECTOR OF ENERGY OF TEMP. CHANGE BY REGION  R  1.7
302      C  SCALE        SCALE FACTOR FOR CONSTANT CURRENT AND POWER R  1.7
303      C
304      C-----
305      C
306      C
307      C O.O  FORTRAN MAIN PROGRAM
308      C
309      C
310      C/  INSERT COMBAS
311      C
312      C      TIME ALLOCATED TO JOB
313      C      CALL JOBTIM(ALTIME)
314      C
315      C      SET UP THE BASIC CONTROL DATA
316      C      CALL BASIC
317      C
318      C      PRINT DATE AND TIME
319      C      CALL PAGE
320      C      CALL DAYTIM
321      C
322      C      CONTROL THE RUN
323      C      CALL COTROL
324      C
325      C      STOP
326      C      END
327      C
328      C
329      C-----
330      C
331      C      SUBROUTINE BASIC
332      C
333      C O.1  INITIALIZE BASIC DATA
334      C
335      C
336      C/  INSERT COMBAS
337      C/  INSERT COMDDP
338      C      DATA          IBLANK/4H      /
339      CL          1.          GENERAL OLYMPUS DATA
340      C
341      CL          1.1          BASIC SYSTEM PARAMETERS
342      C      CPU - TIME USED SO FAR
343      C      CPTIME=0.0
344      C
345      C      CLEAR ALL 8 LABEL ARRAYS
346      C      IL = 8 * 12
347      C      CALL RESETH(LABEL1,IL,IBLANK)
348      C
349      C      INPUT-OUTPUT CHANNELS
350      C      NLEDGE = 30
351      C      NONLIN = 1
352      C      NPUNCH=7
353      C      NPRINT=6
354      C      NREAD=5
355      C      NDIARY=NPRINT
356      C      NIN=NREAD
357      C      NOUT=NPRINT
358      C
359      C      TIMESTEP CONTROL
360      C      NRUN = 1

```



```

361          NSTEP=0
362      C
363      C      RESTART CONTROL
364          NREC = 1
365          NRESUM = NLEDGE
366      C
367      C      LOGICAL SWITCHES
368          NLEND=.FALSE.
369          NLRES=.FALSE.
370      C
371      CL          1.9          DIAGNOSTIC AND DEVELOPMENT PARAMETERS
372          MAXDUM = 20
373      C      MAXIMUM DIMENSIONS OF DUMP ARRAYS
374          MXDUMP = 10
375      C      RESET DUMP ARRAYS
376          CALL RESETI(NADUMP,MAXDUM,0)
377          CALL RESETI(NPDUMP,MAXDUM,0)
378          CALL RESETI(NVDUMP,MAXDUM,0)
379      C      TRACER VARIABLES
380          NCLASS = 0
381          NSUB = 1
382          NPOINT = 1
383      C      LOGICAL SWITCHES
384          NLCHED = .FALSE.
385          NLREPT = .FALSE.
386      C      REPORT HEADS FOR CLASSES 1-9
387          CALL RESETL(NLHEAD,9,.FALSE.)
388      C      RESET CLASS 1,2,3 SUBPROGRAM SELECTOR ARRAY
389          CALL RESETL(NLOMT1,50,.FALSE.)
390          CALL RESETL(NLOMT2,50,.FALSE.)
391          CALL RESETL(NLOMT3,50,.FALSE.)
392      C
393      C      USER INTERFACE
394          CALL MODIFY
395      C
396          RETURN
397      END
398      C
399      C-----
400      C
401          SUBROUTINE MODIFY
402      C
403      C O.2  MODIFY BASIC DATA IF REQUIRED
404      C
405      C/  INSERT COMBAS
406      C/  INSERT COMDDP
407      C
408          NAMELIST/INMOD/NONLIN,NRUN,NREC,NRESUM,NLRES
409      C
410      C      PRINT USER, TIME AND DATE TO DIARY FILE
411          CALL USER
412      C
413      C      SET DEFAULT VALUE FOR NRESUM
414          NRESUM=2
415      C
416      C      INPUT NAMELIST TO MODIFY BASIC DATA
417          READ(NREAD,INMOD)
418          IF(.NOT.NLRES) NREC=1
419          RETURN
420      END

```



```

421 C
422 C-----
423 C
424 SUBROUTINE COTROL
425 C
426 C O.3 CONTROL THE RUN
427 C
428 C VERSION 2B 17/12/73 KVR/MHH CULHAM
429 C
430 C/ INSERT COMBAS
431 C/ INSERT COMDDP
432 CL 1. PROLOGUE
433 C
434 IF(NLRES) GO TO 170
435 C
436 C A. NEW RUN
437 C
438 CL 1.1 LABEL THE RUN
439 110 CALL LABRUN
440 C
441 CL 1.2 CLEAR VARIABLES AND ARRAYS
442 120 CALL CLEAR
443 C
444 CL 1.3 SET DEFAULT VALUES
445 130 CALL PRESET
446 C
447 CL 1.4 DEFINE DATA SPECIFIC TO RUN
448 140 CALL DATA
449 C
450 CL 1.5 SET AUXILIARY VALUES
451 150 CALL AUXVAL
452 C
453 CL 1.6 DEFINE PHYSICAL INITIAL CONDITIONS
454 160 CALL INITAL
455 GO TO 180
456 C
457 C B. RESUME A PREVIOUS RUN
458 C
459 CL 1.7 PICK UP RECORD, MODIFY REQUIRED PARAMETERS
460 170 CONTINUE
461 C LABEL THE CONTINUATION RUN
462 CALL LABRUN
463 C CLEAR VARIABLES AND ARRAYS
464 CALL CLEAR
465 C PICK UP RECORD AND PRINT DETAILS
466 CALL RESUME
467 C READ ANY NEW DATA NEEDED
468 CALL DATA
469 C MODIFY AUXILIARY VARIABLES AS REQUIRED
470 CALL AUXVAL
471 C
472 C C. PRELIMINARY OPERATIONS
473 C
474 CL 1.8 START OR RESTART THE RUN
475 180 CALL START
476 C INITIAL OUTPUT
477 CALL OUTPUT(1)
478 C
479 C
480 CL 2. CALCULATION

```



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481 C
482 CL          2.1      STEP ON THE CALCULATION
483   210      CALL STEPON
484 C
485 CL          3.      OUTPUT
486 C
487 CL          3.1      PERIODIC PRODUCTION OF OUTPUT
488   310      CALL OUTPUT(2)
489 C
490 CL          4.      EPILOGUE
491 C
492 CL          4.1      TEST FOR COMPLETION OF RUN
493   410      CALL TESEND
494           IF(.NOT.NLEND) GO TO 210
495 C
496 C      FINAL OUTPUT
497           CALL OUTPUT(3)
498 C
499 CL          4.2      TERMINATE THE RUN
500   420      CALL ENDRUN
501 C
502           RETURN
503           END
504 C
505 C-----
506 C
507           SUBROUTINE USER
508 C
509 C 0.4 LOG USER CSID, TIME AND DATE TO DIARY FILE
510 C
511           INTEGER*4 INAME, ITIME(2), IDATE(3)
512           CALL GUINFO('SIGNONID',INAME)
513           CALL TIME(4,0,ITIME)
514           CALL TIME(5,0,IDATE)
515           CALL FTNCMD('ASSIGN 18=HADI:ULOG',19)
516           WRITE(18,20) INAME,ITIME(1),ITIME(2),(IDATE(J),J=1,3)
517   20      FORMAT(' MEGAERA',5X,A4,5X,2A4,5X,3A4)
518           RETURN
519           END
520 C
521 C-----
522 C
523           SUBROUTINE LABRUN
524 C
525 C 1.1 LABEL THE RUN
526 C
527 C/ INSERT COMBAS
528           NAMelist/LABELS/LABEL1,LABEL2,LABEL3,LABEL4
529 C
530 C      READ IN LABELS
531           READ(NREAD,LABELS)
532 C
533 C      PRINT PROGRAM HEADING AND LABELS
534           CALL BLINES(3)
535           WRITE(NPRINT,20)
536           WRITE(NPRINT,21)
537           WRITE(NPRINT,22)
538           CALL BLINES(2)
539           CALL MESSAGE(LABEL1)
540           CALL MESSAGE(LABEL2)

```



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541          CALL MESSAGE(LABEL3)
542          CALL MESSAGE(LABEL4)
543          RETURN
544      C
545      C
546      20      FORMAT(35X,'P R O G R A M   M E G A E R A')
547      21      FORMAT(35X,'-----')
548      22      FORMAT('O',34X,'ADH',14X,'AUGUST, 1980')
549      C
550          END
551      C
552      C-----
553      C
554          SUBROUTINE CLEAR
555      C
556      C 1.2  CLEAR VARIABLES AND ARRAYS
557      C
558      C
559      C/ INSERT COMGLO
560      C/ INSERT COMELE
561      C/ INSERT COMTHM
562      C/ INSERT COMTEM
563      C/ INSERT COMCON
564      C/ INSERT COMDIM
565      C
566          NDX=50
567          NDY=50
568          NV=NDX
569          IF(NDY.GT.NDX) NV=NDY
570          NA=NDX*NDY
571      C
572      C      CLEAR GLOBAL VARIABLES
573          IL=6 * NA + 4 * NV + 7
574          CALL RESETR(ELECON,IL,O.O)
575      C
576      C      CLEAR ELECTRICAL COMMON BLOCKS
577          IL= 7 * NA + 3 * 10 + 1 * NV
578          CALL RESETR(ECXP,IL,O.O)
579      C
580      C      CLEAR THERMAL COMMON BLOCK
581          IL= 3 * 10 + 7 * NA
582          CALL RESETR(THMCON,IL,O.O)
583      C
584      C      CLEAR TEMPERARY ARRAYS
585          IL= 3 * NA + 5 * NV
586          CALL RESETR(TEM1,IL,O.O)
587      C
588      C      CLEAR TIMESTEP CONTROL COMMON BLOCK
589          IL= 38
590          CALL RESETR(HTIME,IL,O.O)
591      C
592      C      CLEAR INTEGER VARIABLES
593          IL= 18
594          CALL RESETI(NX,IL,O)
595      C
596          RETURN
597          END
598      C
599      C-----
600      C

```



```

601          SUBROUTINE PRESET
602      C
603      C 1.3  SET DEFAULT VALUES
604      C
605      C/ INSERT COMDIM
606      C/ INSERT COMELE
607      C/ INSERT COMCON
608      C/ INSERT COMGLO
609      C
610      C      THE ELECTRICAL AND THERMAL GEOMETRY DEFAULTS TO INSULATORS.
611      C      THIS HAS BEEN PRESET BY SETTING THE ARRAYS ELEGEO AND
612      C      THMGEO TO ZERO ( AS DONE IN SUBROUTINE CLEAR ).
613      C
614          NDX=50
615          NDY=50
616          EPSELE=1.E+6
617          SCALE=1.0
618          THICK=1.0
619          MMAX=200
620          NSPO=1
621          NERROR=0
622          NPX=20
623          NPY=20
624          NIJ=1
625          NCI=0
626          NSTO=1000
627      C
628          RETURN
629          END
630      C
631      C-----
632      C
633          SUBROUTINE DATA
634      C
635      C 1.4  DEFINE DATA SPECIFIC TO RUN
636      C
637      C/ INSERT COMGLO
638      C/ INSERT COMELE
639      C/ INSERT COMTHM
640      C/ INSERT COMDIM
641      C/ INSERT COMBAS
642      C/ INSERT COMCON
643      C
644          DATA HHOR,HVER/'HORI','VERT'/,HELE,HINS/'ELEC',
645          #      'INSU'/,HCTE/'CTEM'/
646      C
647      C      NAMELISTS
648          NAMELIST /INPUT1/
649          #      NX,NY,DELTAX,DELTAY,THICK,GEOMET,NREG
650          NAMELIST /REGION/
651          #      MINI,MAXI,MINJ,MAXJ,EALPHA,EBETA,THMK,
652          #      THMRC,ETYPE,TTYPE,VOLTS,TEMPER
653          NAMELIST /INPUT2/
654          #      XMIN,XMAX,YMIN,YMAX,NSPO,NSTO,NPX,NPY
655          NAMELIST /INPUT3/
656          #      TINIT,DTIME,HTIME,NTYPE,CCUR,CPOW,CTIME,
657          #      DTEMP,NIJ,NCI,CVOL,EPSELE,MMAX
658      C
659      C      RESUMING AN OLD RUN?
660          IF(NLRES) GOTO 10

```



```

661      C
662      C      READ IN FIRST NAMELIST
663      GEOMET=HVER
664      READ(NREAD,INPUT1,END=900)
665      NALPHA=MAX(NX,NY)
666      CALL BLINES(2)
667      CALL OUTR('THICKNESS OF 20 SLICE (THICK)      ',THICK)
668      CALL OUTH('GEOMETRY OF PROBLEM                ',GEOMET)
669      CALL OUTI('NUMBER OF REGIONS (NREG)            ',NREG)
670      IF(NREG.GT.9) GOTO 901
671      NGEO=0
672      IF(GEOMET.EQ.HHOR) NGEO=1
673      C
674      C      READ IN AND OVERLAY DIFFERENT REGIONS
675      DO 1 K=1,NREG
676      READ(NREAD,REGION,END=900)
677      CALL BLINES(2)
678      CALL OUTI('REGION NUMBER                        ',K)
679      C
680      C      FIND ELECTRICAL AND THERMAL REGION TYPES
681      IET=-K
682      IF(ETYPE.EQ.HELE) IET=K
683      IF(ETYPE.EQ.HINS) IET=0
684      ITT=-K
685      IF(TTYPE.EQ.HINS) ITT=0
686      IF(TTYPE.EQ.HCTE) ITT=K
687      C
688      C      OVERLAY ELECTRICAL AND THERMAL GEOMETRIES
689      DO 2 I=MINI,MAXI
690      DO 3 J=MINJ,MAXJ
691      ELEGEO(I,J)=IET
692      THMGEO(I,J)=ITT
693      3      CONTINUE
694      2      CONTINUE
695      C
696      C      STORE ELECTRICAL AND THERMAL PROPERTIES OF THE REGION
697      CALL OUTH('ELECTRICAL TYPE                      ',ETYPE)
698      IF(IET.GE.0) GOTO 4
699      ELEALP(K)=EALPHA
700      ELEBET(K)=EBETA
701      CALL OUTR('TEMP. DEPENDENCE OF CONDUCTIVITY',
702      #      EALPHA)
703      CALL OUTR('CONDUCTIVITY AT 24 CELSIUS          ',EBETA)
704      4      IF(IET.GT.0) ELEVOL(K)=VOLTS
705      IF(IET.GT.0)
706      #      CALL OUTR('VOLTAGE ( BEFORE SCALING )      ',VOLTS)
707      CALL OUTH('THERMAL REGION TYPE                  ',TTYPE)
708      IF(ITT.GE.0) GOTO 5
709      THMCON(K)=THMK
710      THMCAP(K)=THMRC
711      CALL OUTR('THERMAL CONDUCTIVITY                ',
712      #      THMK)
713      CALL OUTR('THERMAL HEAT CAPACITY                ',
714      #      THMRC)
715      5      IF(ITT.GT.0) THMTEM(K)=TEMPER
716      IF(ITT.GT.0)
717      #      CALL OUTR('CONSTANT TEMPERATURE            ',TEMPER)
718      C
719      1      CONTINUE
720      XCOORD(1)=OELTAX(1)/2.

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721          YCOORD(1)=DELTAY(1)/2.
722          DO 6 I=2,NX
723      6          XCOORD(I)=XCOORD(I-1)+(DELTAX(I-1)+DELTAX(I))/2.
724          DO 7 J=2,NY
725      7          YCOORD(J)=YCOORD(J-1)+(DELTAY(J-1)+DELTAY(J))/2.
726          XMIN=XCOORD(1)
727          XMAX=XCOORD(NX)
728          YMIN=YCOORD(1)
729          YMAX=YCOORD(NY)
730      C
731      C      INPUT OUTPUT CONTROL VARIABLES
732          READ(NREAD,INPUT2)
733          CALL BLINES(2)
734          CALL OUTI('NO. OF STEPS PER PRINTED OUTPUT ',NSPO)
735          CALL OUTI('NO. OF STEPS PER TAPE STORAGE ',NSTO)
736          CALL OUTI('NO. OF INTERPOLATION POINTS IN X ',NPX)
737          CALL OUTI('NO. OF INTERPOLATION POINTS IN Y ',NPY)
738          CALL OUTR('X MINIMUM FOR INTERPOLATION ',XMIN)
739          CALL OUTR('X MAXIMUM FOR INTERPOLATION ',XMAX)
740          CALL OUTR('Y MINIMUM FOR INTERPOLATION ',YMIN)
741          CALL OUTR('Y MAXIMUM FOR INTERPOLATION ',YMAX)
742      C
743      C      INPUT HEATING INFORMATION
744      10      READ(NREAD,INPUT3)
745          IF(EPSELE.GT.1.E+4) EPSELE=CVOL/1.E+5
746          DELT=DTEMP
747          IF(NCI.EQ.0) GOTO 902
748          CALL BLINES(3)
749          CALL OUTR('INITIAL TEMPERATURE IN CELSIUS ',TINIT)
750          CALL OUTR('TOTAL HEATING TIME IN SECONDS ',HTIME)
751          CALL OUTR('INITIAL TIMESTEP SIZE IN SECONDS',DTIME)
752          CALL OUTI('GRIDLINE FOR CURRENT INTEGRAL ',NCI)
753          IF(NTYPE.EQ.1)
754      #          CALL OUTR('CONSTANT VOLTAGE ',CVOL)
755          IF(NTYPE.EQ.2)
756      #          CALL OUTR('CONSTANT CURRENT ( AMPERES ) ',CCUR)
757          IF(NTYPE.EQ.3)
758      #          CALL OUTR('CONSTANT POWER ( WATTS ) ',CPOW)
759          CALL OUTR('CHANGE IN TEMPERATURE / TIMESTEP ',DTEMP)
760          CALL OUTI('MAXIMUM NO. OF ITERATIONS (MMAX)',MMAX)
761          CALL OUTR('ELECTRICAL CONVERGENCE CRITERIA ',EPSELE)
762          CALL OUTI('NUMBER OF ITERATION PARAMETERS ',NALPHA)
763          RETURN
764      C
765      C      ERROR MESSAGES
766      900      CALLMESSAGE(48H *** NAMELIST WAS NOT FOUND DURING DATA INPUT )
767          CALL ENDRUN
768          STOP
769      901      CALLMESSAGE(48H *** ONLY NINE REGIONS MAY BE SPECIFIED )
770          CALL ENDRUN
771          STOP
772      902      CALLMESSAGE(48H *** NO SURFACE FOR CURRENT INTEGRAL IS GIVEN )
773          CALL ENDRUN
774          STOP
775          END
776      C
777      C-----
778      C
779          SUBROUTINE AUXVAL
780      C

```



```

781 C 1.5 SET AUXILIARY VALUES
782 C
783 CALL EPARAM
784 CALL TCOEFF
785 C
786 RETURN
787 ENO
788 C
789 C-----
790 C
791 SUBROUTINE INITAL
792 C
793 C 1.6 DEFINE PHYSICAL INITIAL CONDITIONS
794 C
795 C/ INSERT COMGLO
796 C/ INSERT COMDIM
797 C/ INSERT COMCON
798 C/ INSERT COMTHM
799 C
800 C SET INTIAL TEMPERATURE
801 DO 1 J=1,NY
802 DO 1 I=1,NX
803 TEMP(I,J)=TINIT
804 K=THMGEO(I,J)
805 IF(K.GT.O) TEMP(I,J)=THMTEM(K)
806 1 CONTINUE
807 C
808 RETURN
809 END
810 C
811 C-----
812 C
813 SUBROUTINE RESUME
814 C
815 C 1.7 RESUME FROM PREVIOUS RECORO
816 C
817 C/ INSERT COMBAS
818 C/ INSERT COMGLO
819 C/ INSERT COMELE
820 C/ INSERT COMTHM
821 C/ INSERT COMCON
822 C/ INSERT COMDIM
823 C
824 C SET DEFAULT VALUES
825 NDX=50
826 NDY=50
827 SCALE=1.0
828 NERROR=0
829 C
830 C INPUT RECORD OF RUN GEOMETRY AND MATERIAL PROPERTY DATA
831 1 READ(NRESUM,END=900)ELEGE0,THMGEO,DELTAX,DELTAY,THICK,
832 # XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,ELEVOL,
833 # ELEALP,ELEBET,EPSELE,THMCON,THMCAP,THMTEM,
834 # TINIT,NX,NY,NALPHA,MMAX,NREG,NGEO,NSPO,
835 # NSTO,NPX,NPY,NIJ,NCI
836 C
837 C READ UNTIL SPECIFIED RECORO IS INPUT
838 2 READ(NRESUM,END=900)NSTEP,TIME,POTENT,QTHERM,TEMP,TEENG,TENG,
839 # TQENG,QENG,NR,OTIME
840 IF(NR.LT.NREC) GOTO 2

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841             IF(NR.GT.NREC) GOTO 900
842             RETURN
843         C
844         C      RECORD NOT FOUND
845         900    CALLMESSAGE(48H      ***      SPECIFIED RECORD NOT FOUND IN RESUME      )
846             CALL ENDRUN
847             STOP
848             END
849         C
850         C-----
851         C
852             SUBROUTINE START
853         C
854         C 1.8  START OR RESTART THE RUN
855         C
856         C
857             RETURN
858             END
859         C
860         C-----
861         C
862             SUBROUTINE EPARAM
863         C
864         C 1.9  CALCULATE ITERATION PARAMETERS FOR ELECTRICAL A.D.I.P.
865         C
866         C/ INSERT COMELE
867         C/ INSERT COMDIM
868         C
869             DO 3 K=1,NALPHA
870                 ELEPAR(K)=(SIN(K*3.141528/(2.*NALPHA)))*2
871             3    CONTINUE
872         C
873             RETURN
874             END
875         C
876         C-----
877         C
878             SUBROUTINE TCOEFF
879         C
880         C 1.10 CALCULATE THE COEFFICENTS FOR THE HEAT EQUATION
881         C
882         C/ INSERT COMGLO
883         C/ INSERT COMDIM
884         C/ INSERT COMTHM
885         C
886         C      COVER THE GRID
887         DO 1 J=1,NY
888             JP=J+1
889             JM=J-1
890             DY=DELTAY(J)
891         DO 2 I=1,NX
892             IP=I+1
893             IM=I-1
894         C
895         C      CHECK IF THE BLOCK IS IN THE THERMAL DOMAIN
896             K=THMGEO(I,J)
897             IF(K.GE.O) GOTO 2
898         C
899         C      FIND THE THERMAL CONDUCTIVITY AND CLEAR VARIABLES
900             TC=THMCON(-K)

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901          DX=DELTAX(I)
902          TCRHS(I,J)=0.
903          TCX(I,J)=0.
904          TCY(I,J)=0.
905      C
906      C      FIND CDEFFICENTS IN THE X DIRECTION
907      C      CHECK SURRDUNDING BLOCKS
908          KP=0
909          IF(I.LT.NX) KP=THMGEO(IP,J)
910          KM=0
911          IF(I.GT.1) KM=THMGED(IM,J)
912          TCP=TC
913          IF(KP.LT.0) TCP=THMCON(-KP)
914          TCM=TC
915          IF(KM.LT.0) TCM=THMCDN(-KM)
916          RP=TC/TCP
917          RM=TC/TCM
918      C
919      C      DECIDE WHICH CASE THIS GRID BLOCK IS
920      C      1. NDRMAL BLOCK SURROUNDED BY DDMAIN
921          IF(KP.GE.0.OR.KM.GE.0) GOTO 3
922          H=(DX+DELTAX(IP))/2.
923          HM=(DX+DELTAX(IM))/2.
924          TCXP(I,J)=(TC+TCP)/(H*(H+HM))
925          TCXM(I,J)=(TC+TCM)/(HM*(H+HM))
926      C      CHECK FDR CONDUCTIVITY DISCONTINUITIES
927          IF(KP.NE.K)
928      #          TCXP(I,J)=TC/((.25*(H+HM)*(DX+RP*DELTAX(IP)))
929          IF(KM.NE.K)
930      #          TCXM(I,J)=TC/((.25*(H+HM)*(DX+RM*DELTAX(IM)))
931          TCX(I,J)=TCXM(I,J)+TCXP(I,J)
932          GOTO 10
933      C
934      C      2. CONSTANT TEMPERATURE BOUNDARY IN ONE DIRECTIDN
935      3      IF(KP.EQ.0.OR.KM.EQ.0) GDTD 4
936          H=(DX+DELTAX(IP))/2.
937          HM=(DX+DELTAX(IM))/2.
938          IF(KP.GT.0) H=DX/2.
939          IF(KM.GT.0) HM=DX/2.
940          TCXP(I,J)=(TC+TCP)/(H*(H+HM))
941          TCXM(I,J)=(TC+TCM)/(HM*(H+HM))
942          TCX(I,J)=TCXP(I,J)+TCXM(I,J)
943          IF(KP.GT.0) TCRHS(I,J)=TCRHS(I,J)+
944      #          TCXP(I,J)*THMTEM(KP)
945          IF(KP.GT.0) TCXP(I,J)=0.
946          IF(KM.GT.0) TCRHS(I,J)=TCRHS(I,J)+
947      #          TCXM(I,J)*THMTEM(KM)
948          IF(KM.GT.0) TCXM(I,J)=0.
949          GDTD 10
950      C
951      C      3. BOUNDARY IN ONE DIRECTION
952      4      IF(KP.GE.0.AND.KM.GE.0) GOTO 900
953          TCXM(I,J)=0.
954          TCXP(I,J)=0.
955          IF(KP.LT.0) TCXP(I,J)=
956      #          (TC+TCP)/(.5*((DX+DELTAX(IP))**2))
957          IF(KM.LT.0) TCXM(I,J)=
958      #          (TC+TCM)/(.5*((DX+DELTAX(IM))**2))
959          TCX(I,J)=TCXM(I,J)+TCXP(I,J)
960      C

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961      C      CALCULATE COEFFICENTS IN Y DIRECTION
962      10      KP=O
963              IF(J.LT.NY) KP=THMGEO(I,JP)
964              KM=O
965              IF(J.GT.1) KM=THMGEO(I,JM)
966              TCP=TC
967              IF(KP.LT.O) TCP=THMCON(-KP)
968              TCM=TC
969              IF(KM.LT.O) TCM=THMCON(-KM)
970              RP=TC/TCP
971              RM=TC/TCM
972      C
973      C      DECIDE WHICH CASE THIS GRID BLOCK IS
974      C      1. NORMAL BLOCK SURROUNDED BY DOMAIN
975              IF(KP.GE.O.OR.KM.GE.O) GOTO 5
976              H=(DY+DELTAY(JP))/2.
977              HM=(DY+DELTAY(JM))/2.
978              TCYP(I,J)=(TC+TCP)/(H*(H+HM))
979              TCYM(I,J)=(TC+TCM)/(HM*(H+HM))
980      C      CHECK FOR CONDUCTIVITY DISCONTINUITIES
981              IF(KP.NE.K)
982              #      TCYP(I,J)=TC/(.25*(H+HM)*(DY+DELTAY(JP)*RP))
983              IF(KM.NE.K)
984              #      TCYM(I,J)=TC/(.25*(H+HM)*(DY+DELTAY(JM)*RM))
985              TCY(I,J)=TCYM(I,J)+TCYP(I,J)
986              GOTO 2
987      C
988      C      2. CONSTANT TEMPERATURE BOUNDARY
989      5      IF(KP.EQ.O.OR.KM.EQ.O) GOTO 6
990              H=(DY+DELTAY(JP))/2.
991              HM=(DY+DELTAY(JM))/2.
992              IF(KP.GT.O) H=DY/2.
993              IF(KM.GT.O) HM=DY/2.
994              TCYP(I,J)=(TC+TCP)/(H*(H+HM))
995              TCYM(I,J)=(TC+TCM)/(HM*(H+HM))
996              TCY(I,J)=TCYM(I,J)+TCYP(I,J)
997              IF(KP.GT.O) TCRHS(I,J)=TCRHS(I,J)+
998              #      TCYP(I,J)*THMTEM(KP)
999              IF(KP.GT.O) TCYP(I,J)=O.
1000              IF(KM.GT.O) TCRHS(I,J)=TCRHS(I,J)+
1001              #      TCYM(I,J)*THMTEM(KM)
1002              IF(KM.GT.O) TCYM(I,J)=O.
1003              GOTO 2
1004      C
1005      C      3. BOUNDARY IN ONE DIRECTION
1006      6      IF(KP.GE.O.AND.KM.GE.O) GOTO 900
1007              TCYP(I,J)=O.
1008              TCYM(I,J)=O.
1009              IF(KP.LT.O) TCYP(I,J)=
1010              #      (TC+TCP)/(.5*((DY+DELTAY(JP))**2))
1011              IF(KM.LT.O) TCYM(I,J)=
1012              #      (TC+TCM)/(.5*((DY+DELTAY(JM))**2))
1013              TCY(I,J)=TCYM(I,J)+TCYP(I,J)
1014      C
1015      C
1016      2      CONTINUE
1017      1      CONTINUE
1018      RETURN
1019      C
1020      C      ERROR RETURN

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1021      900 CALLMESSAGE(48H      ***      ERROR RETURN FROM ROUTINE TCOEF      )
1022          CALL ENDRUN
1023          RETURN
1024      END
1025      C
1026      C-----
1027      C
1028          SUBROUTINE STEPON
1029      C
1030      C 2.1 STEP ON THE CALCULATION
1031      C
1032      C/ INSERT COMBAS
1033      C/ INSERT COMGLO
1034      C/ INSERT COMCON
1035      C/ INSERT COMDIM
1036          NSTEP=NSTEP+1
1037      C
1038      C
1039      C      IF END OF HEATING PERIOD, RESET ELECTRICAL VARIABLES
1040          IF(ABS(TIME-HTIME).GT.1.) GOTO 1
1041              NTYPE=4
1042              CALL RESETR(POTENT,NDX*NDY,O.O)
1043              CALL RESETR(QTHERM,NDX*NDY,O.O)
1044              VOLTS=O.
1045              POWER=O.
1046              CUR =O.
1047              RESIST=O.
1048      C
1049      C      IF NO HEATING, SKIP E-FIELD AND Q CALCULATIONS
1050      1      IF(NTYPE.EQ.4) GOTO 14
1051      C
1052      C      CALCULATE ELECTRICAL CONDUCTIVITY
1053          CALL ECOND
1054          IF(NERROR.NE.O) RETURN
1055      C
1056      C      DESCALE POTENTIAL AND FIND NEW POTENTIAL
1057          S=1./SCALE
1058          CALL SCALER(POTENT,NDX*NDY,S)
1059          CALL ELEPOT
1060          IF(NERROR.NE.O) RETURN
1061      C
1062      C      SCALE THE POTENTIAL IF CONSTANT CURRENT OR POWER
1063          CALL ELECUR
1064          RESIST=CVOL/CUR
1065          GOTO (10,11,12) ,NTYPE
1066      C
1067      C      CONSTANT VOLTAGE
1068      10      VOLTS=CVOL
1069              POWER=VOLTS*CUR
1070              GOTO 13
1071      C
1072      C      CONSTANT CURRENT
1073      11      SCALE=CCUR/CUR
1074              VOLTS=CVOL*SCALE
1075              CALL SCALER(POTENT,NDX*NDY,SCALE)
1076              POWER=CCUR*VOLTS
1077              CUR=CCUR
1078              GOTO 13
1079      C
1080      C      CONSTANT POWER

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1081      12          SCALE=SQRT(CPOW/(CUR*CVOL))
1082          VOLTS=SCALE*CVOL
1083          POWER=CPOW
1084          CUR=CUR*SCALE
1085          CALL SCALER(POTENT,NDX*NDY,SCALE)
1086      C
1087      C          CALCULATE THE HEATING RATES
1088      13          CALL QCALC
1089          IF(NERROR.NE.O) RETURN
1090      C
1091      C          FIND THE TIMESTEP SIZE FOR THE NEXT HEATING STEP
1092      14          DTIME=DTIME*DTEMP/DELT
1093          IF(NTYPE.LE.3.AND.(DTIME+TIME).GT.(HTIME-1.E-2))
1094      #          DTIME=HTIME-TIME
1095          IF(NTYPE.EQ.4.AND.(DTIME+TIME).GT.(HTIME+CTIME))
1096      #          DTIME=HTIME+CTIME-TIME
1097      C
1098      C          FIND THE NEW TEMPERATURE
1099          CALL TCALC
1100          IF(NERROR.NE.O) RETURN
1101      C
1102      C          CHECK THE ENERGY BALANCE
1103          CALL ENGBAL
1104          TIME=TIME+DTIME
1105          RETURN
1106      END
1107      C
1108      C-----
1109      C
1110          SUBROUTINE ELEPOT
1111      C
1112      C  2.2  CALCULATE THE ELECTRICAL POTENTIAL FROM THE
1113      C        FINITE DIFFERENCE EQUATION, USING THE
1114      C        ALTERNATING DIRECTION IMPLICIT PROCEDURE.
1115      C
1116      C/  INSERT COMGLO
1117      C/  INSERT COMELE
1118      C/  INSERT COMTEM
1119      C/  INSERT COMDIM
1120      C
1121      C          FIRST, CALCULATE THE COEFFICENTS FOR THIS TIME STEP
1122          CALL ELECOF
1123          IF(NERROR.NE.O) RETURN
1124      C
1125      C          USE THE POTENTIAL OF THE LAST STEP AS THE FIRST GUESS
1126          CALL COPYR(POTENT,1,TEM1,1,NDX*NDY)
1127      C
1128      C          RESET THE ITERATION COUNTER
1129          MITER=0
1130      C
1131      C  ***  START OF ITERATION LOOP FOR A.D.I.P.  ***
1132      1          MITER=MITER+1
1133      C
1134      C          CHECK IF THE MAXIMUM NUMBER OF ITERATIONS IS REACHED
1135          IF(MITER.GT.MMAX) GOTO 900
1136      C
1137      C          CHOOSE THE ITERATION PARAMETER
1138          L=MITER-(MITER/NALPHA)*NALPHA
1139          IF(L.EQ.O) L=NALPHA
1140          ALPHA=ELEPAR(L)

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1141 C
1142 C FIRST STAGE, IMPLICIT IN X.
1143 DO 2 J=1,NY
1144     JM=J-1
1145     IF(J.EQ.1) JM=1
1146     JP=J+1
1147     IF(J.EQ.NY) JP=NY
1148     NEQU=0
1149     DO 3 I=1,NX
1150 C
1151 C IF THE BLOCK IS AN ELECTRODE, OR NOT IN THE DOMAIN,
1152 C SKIP TO THE NEXT BLOCK.
1153     K=ELEGEO(I,J)
1154     IF(K.GE.O) GOTO 3
1155 C
1156 C CALCULATE AND ASSIGN TRIDIAGONAL COEFFICENTS
1157     NEQU=NEQU+1
1158     ECSUM=EXMXP(I,J)+EYMYP(I,J)
1159     T1(NEQU)=ECXM(I,J)
1160     T2(NEQU)=- (EXMXP(I,J)+ALPHA*ECSUM)
1161     T3(NEQU)=ECXP(I,J)
1162     T4(NEQU)=- (ECYM(I,J)*TEM1(I,JM)+ECYP(I,J)*TEM1(I,JP))
1163     #           + (EYMYP(I,J)-ALPHA*ECSUM)*TEM1(I,J)
1164     #           -ERHS(I,J)
1165 3 CONTINUE
1166 C
1167 C SOLVE THE TRIDIAGONAL SYSTEM
1168     CALL THOMAS
1169 C
1170 C PLACE RESULTS IN TEM2
1171     NEQU=0
1172     DO 5 I=1,NX
1173         TEM2(I,J)=0.
1174         K=ELEGEO(I,J)
1175         IF(K.GE.O) GOTO 5
1176         NEQU=NEQU+1
1177         TEM2(I,J)=T5(NEQU)
1178 5 CONTINUE
1179 C
1180 2 CONTINUE
1181 C
1182 C START OF SECOND STAGE
1183 DO 6 I=1,NX
1184     IM=I-1
1185     IF(I.EQ.1) IM=I
1186     IP=I+1
1187     IF(I.EQ.NX) IP=I
1188     NEQU=0
1189     DO 7 J=1,NY
1190 C
1191 C IF NOT IN DOMAIN, SKIP TO NEXT POINT
1192     K=ELEGEO(I,J)
1193     IF(K.GE.O) GOTO 7
1194 C
1195 C CALCULATE AND ASSIGN TRIDIAGONAL COEFFICENTS
1196     NEQU=NEQU+1
1197     ECSUM=EXMXP(I,J)+EYMYP(I,J)
1198     T1(NEQU)=ECYM(I,J)
1199     T2(NEQU)=- (EYMYP(I,J)+ALPHA*ECSUM)
1200     T3(NEQU)=ECYP(I,J)

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1201          T4(NEQU)=- (ECXM(I,J)*TEM2(IM,J)+ECXP(I,J)*TEM2(IP,J))
1202          #          +(EXMXP(I,J)-ALPHA*ECSUM)*TEM2(I,J)
1203          #          -ERHS(I,J)
1204      7      CONTINUE
1205      C
1206      C      SOLVE TRIDIAGONAL SYSTEM
1207      C      CALL THOMAS
1208      C
1209      C      PLACE RESULTS IN TEM3
1210      C      NEQU=0
1211      C      DO 9 J=1,NY
1212      C          TEM3(I,J)=0.
1213      C          K=ELEGE0(I,J)
1214      C          IF(K.GT.O) TEM3(I,J)=ELEVOL(K)
1215      C          IF(K.GE.O) GOTO 9
1216      C          NEQU=NEQU+1
1217      C          TEM3(I,J)=T5(NEQU)
1218      9      CONTINUE
1219      C
1220      6      CONTINUE
1221      C
1222      C      CHECK FOR CONVERGENCE
1223      C      CALL MAXDIF(1,EPS)
1224      C          IF(EPS.LT.EPSELE) GOTO 10
1225      C
1226      C      NO CONVERGENCE, TRANSFERE TEM3 TO TEM1
1227      C      CALL COPYR(TEM3,1,TEM1,1,NDX*NDY)
1228      C
1229      C      LOOP BACK TO START NEXT ITERATION
1230      C      GOTO 1
1231      C
1232      C      *** END OF ITERATION LOOP ***
1233      C
1234      C      TRANSFERE FINAL SOLUTION TO POTENT
1235      10      CALL COPYR(TEM3,1,POTENT,1,NDX*NDY)
1236      C      RETURN
1237      C
1238      C      ERROR MESSAGE - SOLUTION FAILED TO CONVERGE
1239      900.      NERROR=1
1240      C      CALL COPYR(TEM3,1,POTENT,1,NDX*NDY)
1241      C      RETURN
1242      C      END
1243      C
1244      C-----
1245      C
1246      C      SUBROUTINE ELECOF
1247      C
1248      C      2.3 CALCULATION OF COEFFICENTS OF ELECTRICAL DIFFERENCE EQU.
1249      C
1250      C/ INSERT COMGLO
1251      C/ INSERT COMELE
1252      C/ INSERT COMDIM
1253      C
1254      C      FOR EACH GRID BLOCK, CALCULATE THE FOUR COEFFICENTS
1255      C      DO 1 J=1,NY
1256      C          DY=DELTAY(J)
1257      C          DO 2 I=1,NX
1258      C      IF BLOCK NOT IN DOMAIN, THEN SKIP TO NEXT BLOCK
1259      C          K=ELEGE0(I,J)
1260      C          IF(K.GE.O) GOTO 2

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1261      C
1262          ERHS(I,J)=0.
1263          EXMXP(I,J)=0.
1264          EYMP(I,J)=0.
1265          DX=DELTA(I)
1266          S=ELECDN(I,J)
1267      C
1268      C      CALCULATE COEFFICENTS FOR X DIRECTIDN
1269      C      CHECK SURROUNDING BLOCKS
1270          KP=0
1271          IF(I.LT.NX) KP=ELEGED(I+1,J)
1272          KM=0
1273          IF(I.GT.1) KM=ELEGED(I-1,J)
1274          SP=S
1275          IF(KP.LT.O) SP=ELECON(I+1,J)
1276          SM=S
1277          IF(KM.LT.O) SM=ELECDN(I-1,J)
1278          RP=S/SP
1279          RM=S/SM
1280      C
1281      C      DECIDE WHICH CASE THIS GRID BLDCK IS
1282      C      1. NORMAL BLDCK SURRDUNDED BY DOMAIN
1283          IF(KP.GE.O.OR.KM.GE.O) GDTD 3
1284              H=(DX+DELTA(I+1))/2.
1285              HM=(DX+DELTA(I-1))/2.
1286              ECXP(I,J)=(S+SP)/(H*(H+HM))
1287              ECXM(I,J)=(S+SM)/(HM*(H+HM))
1288      C      CHECK FOR CONDUCTIVITY DISCDNTINUITIES
1289          IF(KP.NE.K)
1290      #          ECXP(I,J)=S/(.25*(H+HM)*(DX+RP*DELTA(I+1)))
1291          IF(KM.NE.K)
1292      #          ECXM(I,J)=S/(.25*(H+HM)*(DX+RM*DELTA(I-1)))
1293          EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1294          GOTO 10
1295      C
1296      C      2. ELECTRODE IN ONE DIRECTIDN
1297      3      IF(KP.EQ.O.OR.KM.EQ.O) GDTD 4
1298          H=(DX+DELTA(I+1))/2.
1299          HM=(DX+DELTA(I-1))/2.
1300          IF(KP.GT.O) H=DX/2.
1301          IF(KM.GT.O) HM=DX/2.
1302          ECXP(I,J)=(S+SP)/(H*(H+HM))
1303          ECXM(I,J)=(S+SM)/(HM*(H+HM))
1304          EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1305          IF(KP.GT.O) ERHS(I,J)=ERHS(I,J)+
1306      #          ECXP(I,J)*ELEVOL(KP)
1307          IF(KP.GT.O) ECXP(I,J)=0.
1308          IF(KM.GT.O) ERHS(I,J)=ERHS(I,J)+
1309      #          ECXM(I,J)*ELEVDL(KM)
1310          IF(KM.GT.O) ECXM(I,J)=0.
1311          GDTD 10
1312      C
1313      C      3. BDUNDARY IN DNE DIRECTIDN
1314      4      IF(KP.GE.O.AND.KM.GE.O) GDTD 900
1315          ECXM(I,J)=0.
1316          ECXP(I,J)=0.
1317          IF(KP.LT.O) ECXP(I,J)=
1318      #          (S+SP)/(.5*((DX+DELTA(I+1))**2))
1319          IF(KM.LT.O) ECXM(I,J)=
1320      #          (S+SM)/(.5*((DX+DELTA(I-1))**2))

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1321             EXMXP(I,J)=ECXM(I,J)+ECXP(I,J)
1322 C
1323 C      CALCULATE COEFFICIENTS IN THE Y DIRECTION
1324 10      KP=0
1325             IF(J.LT.NY) KP=ELEGEO(I,J+1)
1326             KM=0
1327             IF(J.GT.1) KM=ELEGEO(I,J-1)
1328             SP=S
1329             IF(KP.LT.0) SP=ELECON(I,J+1)
1330             SM=S
1331             IF(KM.LT.0) SM=ELECON(I,J-1)
1332             RP=S/SP
1333             RM=S/SM
1334 C
1335 C      DECIDE WHICH CASE THIS GRID BLOCK IS
1336 C      1. NORMAL BLOCK SURROUNDED BY DOMAIN
1337             IF(KP.GE.0.OR.KM.GE.0) GOTO 5
1338             H=(DY+DELTAY(J+1))/2.
1339             HM=(DY+DELTAY(J-1))/2.
1340             ECYP(I,J)=(S+SP)/(H*(H+HM))
1341             ECYM(I,J)=(S+SM)/(HM*(H+HM))
1342 C      CHECK FOR CONDUCTIVITY DISCONTINUITIES
1343             IF(KP.NE.K)
1344 #             ECYP(I,J)=S/ (.25*(H+HM)*(DY+RP*DELTAY(J+1)))
1345             IF(KM.NE.K)
1346 #             ECYM(I,J)=S/ (.25*(H+HM)*(DY+RM*DELTAY(J-1)))
1347             EYMP(I,J)=ECYM(I,J)+ECYP(I,J)
1348             GOTO 2
1349 C
1350 C      2. ELECTRODE IN ONE DIRECTION
1351 5      IF(KP.EQ.0.OR.KM.EQ.0) GOTO 6
1352             H=(DY+DELTAY(J+1))/2.
1353             HM=(DY+DELTAY(J-1))/2.
1354             IF(KP.GT.0) H=DY/2.
1355             IF(KM.GT.0) HM=DY/2.
1356             ECYP(I,J)=(S+SP)/(H*(H+HM))
1357             ECYM(I,J)=(S+SM)/(HM*(H+HM))
1358             EYMP(I,J)=ECYM(I,J)+ECYP(I,J)
1359             IF(KP.GT.0) ERHS(I,J)=ERHS(I,J)+
1360 #             ECYP(I,J)*ELEVOL(KP)
1361             IF(KP.GT.0) ECYP(I,J)=0.
1362             IF(KM.GT.0) ERHS(I,J)=ERHS(I,J)+
1363 #             ECYM(I,J)*ELEVOL(KM)
1364             IF(KM.GT.0) ECYM(I,J)=0.
1365             GOTO 2
1366 C
1367 C      3. BOUNDARY IN ONE DIRECTION
1368 6      IF(KP.GE.0.AND.KM.GE.0) GOTO 900
1369             ECYM(I,J)=0.
1370             ECYP(I,J)=0.
1371             IF(KP.LT.0) ECYP(I,J)=
1372 #             (S+SP)/ (.5*((DY+DELTAY(J+1))**2))
1373             IF(KM.LT.0) ECYM(I,J)=
1374 #             (S+SM)/ (.5*((DY+DELTAY(J-1))**2))
1375             EYMP(I,J)=ECYM(I,J)+ECYP(I,J)
1376 C
1377 C
1378 2      CONTINUE
1379 1      CONTINUE
1380      RETURN

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1381 C
1382 C      ERROR RETURN
1383 900      NERROR=4
1384          RETURN
1385          END
1386 C
1387 C-----
1388 C
1389          SUBROUTINE THOMAS
1390 C
1391 C      2.4  SOLVE A TRIDIAGONAL SYSTEM BY THOMAS'S ALGORITHM
1392 C
1393 C/  INSERT COMTEM
1394 C/  INSERT COMDIM
1395 C
1396          DIMENSION W(50),G(50)
1397 C
1398          W(1)=T3(1)/T2(1)
1399          G(1)=T4(1)/T2(1)
1400 C
1401          DO 1 I=2,NEQU
1402              IM=I-1
1403              DENOM=T2(I)-T1(I)*W(IM)
1404              W(I)=T3(I)/DENOM
1405              G(I)=(T4(I)-T1(I)*G(IM))/DENOM
1406 1          CONTINUE
1407 C
1408          T5(NEQU)=G(NEQU)
1409          DO 2 I=2,NEQU
1410              I1=NEQU+1-I
1411              IP=I1+1
1412              T5(I1)=G(I1)-W(I1)*T5(IP)
1413 2          CONTINUE
1414 C
1415          RETURN
1416          END
1417 C
1418 C-----
1419 C
1420          SUBROUTINE MAXDIF(ICODE,EPS)
1421 C
1422 C      2.5  FIND THE MAXIMUM DIFFERENCE BETWEEN TEM3, TEM1
1423 C
1424 C/  INSERT COMTEM
1425 C/  INSERT COMDIM
1426 C/  INSERT COMGLO
1427 C
1428 C
1429          EPS=0.
1430          DO 1 J=1,NY
1431              DO 2 I=1,NX
1432                  IF(ICODE.EQ.1) K=ELEGEO(I,J)
1433                  IF(ICODE.EQ.2) K=THMGEO(I,J)
1434                  IF(K.GE.0) GOTO 2
1435                  DIF=ABS(TEM3(I,J)-TEM1(I,J))
1436                  IF(ICODE.EQ.2)
1437                      #      DIF=DIF/ABS(TEM1(I,J))
1438                  EPS=AMAX1(DIF,EPS)
1439 2          CONTINUE
1440 1          CONTINUE

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1441         RETURN
1442         END
1443     C
1444     C-----
1445     C
1446         SUBROUTINE ECONC
1447     C
1448     C 2.6 CALCULATE THE ELECTRICAL CONDUCTIVITY
1449     C
1450     C THE ELECTRICAL CONDUCTIVITY IS ASSUMED TO BE TEMPERATURE
1451     C DEPENDENT, ACCORDING TO THE FORMULA;
1452     C
1453     C SIGMA(T)=BETA(1+ALPHA(T-24))
1454     C
1455     C WHERE T IS IN DEGREES CELCIUS.
1456     C
1457     C/ INSERT COMGLO
1458     C/ INSERT COMELE
1459     C/ INSERT COMDIM
1460     C
1461     C
1462         DO 1 J=1,NY
1463             DO 2 I=1,NX
1464                 K=ELEGEO(I,J)
1465                 IF(K.GE.O) GOTO 2
1466     C
1467     C FIND THE COEFFICENTS FOR THE CONDUCTIVITY
1468         K=-K
1469         ALPHA=ELEALP(K)
1470         BETA=ELEBET(K)
1471         T=TEMP(I,J)
1472     C
1473         ELECON(I,J)=BETA*(1.+ALPHA*(T-24.))
1474     C
1475     2 CONTINUE
1476     1 CONTINUE
1477     RETURN
1478     END
1479     C
1480     C-----
1481     C
1482         SUBROUTINE QCALC
1483     C
1484     C 2.7 CALCULATE THE HEATING RATE AT EACH GRIDPOINT.
1485     C
1486     C/ INSERT COMDIM
1487     C/ INSERT COMGLO
1488     C
1489     C FOR EACH GRID POINT
1490         DO 80 J=1,NY
1491             JP=J+1
1492             JM=J-1
1493             DO 81 I=1,NX
1494                 IM=I-1
1495                 IP=I+1
1496                 QTHERM(I,J)=0.
1497     C
1498     C CHECK IF THIS GRIDBLOCK IS IN THE DOMAIN
1499         K=ELEGEO(I,J)
1500         IF(K.GE.O) GOTO 81

```



```

1501 C
1502 C CHECK BLOCKS IN THE X DIRECTION
1503 KP=0
1504 IF(I.LT.NX) KP=ELEGEO(IP,J)
1505 KM=0
1506 IF(I.GT.1) KM=ELEGEO(IM,J)
1507 C
1508 C CALCULATION WHEN SURROUNDING BLOCKS ARE DOMAIN BLOCKS
1509 IF(KP.EQ.O.OR.KM.EQ.O.OR.(KP.NE.K.AND.KM.EQ.K.AND
1510 # .KP.LT.O).OR.(KM.NE.K.AND.KP.EQ.K.AND.KM.LT.O))GOTO 2
1511 H=(DELTAX(I)+DELTAX(IP))/2.
1512 HM=(DELTAX(I)+DELTAX(IM))/2.
1513 IF(KP.GT.O) H=DELTAX(I)/2.
1514 IF(KM.GT.O) HM=DELTAX(I)/2.
1515 HS=H**2
1516 HMS=HM**2
1517 EX=(POTENT(IP,J)*HMS+(HS-HMS)*POTENT(I,J)
1518 # -POTENT(IM,J)*HS)/(H*HM*(H+HM))
1519 GOTO 3
1520 C
1521 C SPECIAL CASES
1522 2 IF(KP.GE.O.AND.KM.GE.O) GOTO 900
1523 IF((KP.EQ.O.AND.KM.LT.O).OR.KM.EQ.K)
1524 # EX=(2./(DELTAX(I)+DELTAX(IM)))*(POTENT(I,J)-POTENT(IM,J))
1525 IF((KP.LT.O.AND.KM.EQ.O).OR.KP.EQ.K)
1526 # EX=(2./(DELTAX(I)+DELTAX(IP)))*(POTENT(IP,J)-POTENT(I,J))
1527 C
1528 3 CONTINUE
1529 C
1530 C CHECK BLOCKS IN THE Y DIRECTION
1531 KP=0
1532 IF(J.LT.NY) KP=ELEGEO(I,JP)
1533 KM=0
1534 IF(J.GT.1) KM=ELEGEO(I,JM)
1535 C
1536 C CALCULATION WHEN SURROUNDED BY DOMAIN BLOCKS
1537 IF(KP.EQ.O.OR.KM.EQ.O.OR.(KP.NE.K.AND.KM.EQ.K.AND
1538 # .KP.LT.O).OR.(KM.NE.K.AND.KP.EQ.K.AND.KM.LT.O))GOTO 4
1539 H=(DELTAY(J)+DELTAY(JP))/2.
1540 HM=(DELTAY(J)+DELTAY(JM))/2.
1541 IF(KP.GT.O) H=DELTAY(J)/2.
1542 IF(KM.GT.O) HM=DELTAY(J)/2.
1543 HS=H**2
1544 HMS=HM**2
1545 EY=(POTENT(I,JP)*HMS+(HS-HMS)*POTENT(I,J)
1546 # -POTENT(I,JM)*HS)/(H*HM*(H+HM))
1547 GOTO 5
1548 C
1549 C SPECIAL CASES
1550 4 IF(KP.GE.O.AND.KM.GE.O) GOTO 900
1551 IF((KP.EQ.O.AND.KM.LT.O).OR.KM.EQ.K)
1552 # EY=(2./(DELTAY(J)+DELTAY(JM)))*(POTENT(I,J)-POTENT(I,JM))
1553 IF((KP.LT.O.AND.KM.EQ.O).OR.KP.EQ.K)
1554 # EY=(2./(DELTAY(J)+DELTAY(JP)))*(POTENT(I,JP)-POTENT(I,J))
1555 C
1556 5 CONTINUE
1557 C
1558 C CALCULATE HEATING
1559 QTHERM(I,J)=ELECON(I,J)*(EX**2+EY**2)
1560 C

```



```

1561      81          CONTINUE
1562      80          CONTINUE
1563          RETURN
1564      C
1565      C          ERROR RETURN
1566      900          NERROR=2
1567          RETURN
1568          END
1569      C
1570      C-----
1571      C
1572          SUBROUTINE TCALC
1573      C
1574      C  2.8  SOLVE THE TEMPERATURE EQUATION
1575      C
1576      C/ INSERT COMGLO
1577      C/ INSERT COMTHM
1578      C/ INSERT COMTEM
1579      C/ INSERT COMCON
1580      C/ INSERT COMDIM
1581      C
1582      C          COPY THE TEMPERATURE INTO TEM1
1583          CALL COPYR(TEMP,1,TEM1,1,NDX*NDY)
1584      C
1585          M=0
1586      B          M=M+1
1587      C
1588      C          START OF FIRST STAGE
1589      DO 1 J=1,NY
1590          JM=J-1
1591          IF(J.EQ.1) JM=1
1592          JP=J+1
1593          IF(J.EQ.NY) JP=NY
1594          NEQU=0
1595          DO 2 I=1,NX
1596      C
1597      C          IF BLOCK IS NOT IN DOMAIN, SKIP TO NEXT BLOCK
1598          K=THMGEO(I,J)
1599          IF(K.GE.O) GOTO 2
1600          F1=THMCAP(-K)/(DTIME/2.)
1601      C
1602      C          ASSIGN TRIDIAGONAL COEFFICENTS
1603          NEQU=NEQU+1
1604          T1(NEQU)=TCXM(I,J)
1605          T2(NEQU)=- (TCX(I,J)+F1)
1606          T3(NEQU)=TCXP(I,J)
1607          T4(NEQU)=- (TCYM(I,J)*TEM1(I,JM)+TCYP(I,J)*TEM1(I,JP))
1608          #          + (TCY(I,J)-F1)*TEM1(I,J)-TCRHS(I,J)
1609          #          -QTHERM(I,J)
1610      2          CONTINUE
1611      C
1612      C          SOLVE TRIDIAGONAL SYSTEM
1613          CALL THOMAS
1614      C
1615      C          PLACE RESULTS IN TEM2
1616          NEQU=0
1617          DO 3 I=1,NX
1618          TEM2(I,J)=0.
1619          K=THMGEO(I,J)
1620          IF(K.GE.O) GOTO 3

```



```

1621             NEQU=NEQU+1
1622             TEM2(I,J)=T5(NEQU)
1623     3         CONTINUE
1624     C
1625     1         CONTINUE
1626     C
1627     C         START OF SECOND STAGE
1628     DO 4 I=1,NX
1629             IP=I+1
1630             IF(I.EQ.NX) IP=NX
1631             IM=I-1
1632             IF(I.EQ.1) IM=I
1633             NEQU=0
1634             DO 5 J=1,NY
1635     C
1636     C         IF BLOCK NOT IN DOMAIN, SKIP TO NEXT BLOCK
1637             K=THMGEO(I,J)
1638             IF(K.GE.O) GOTO 5
1639     C
1640     C         ASSIGN TRIDIAGONAL COEFFICENTS
1641             F1=THMCAP(-K)/(DTIME/2.)
1642             NEQU=NEQU+1
1643             T1(NEQU)=TCYM(I,J)
1644             T2(NEQU)=-(TCY(I,J)+F1)
1645             T3(NEQU)=TCYP(I,J)
1646             T4(NEQU)=-(TCXM(I,J)*TEM2(IM,J)+TCXP(I,J)*TEM2(IP,J))
1647             #             +(TCX(I,J)-F1)*TEM2(I,J)-TCRHS(I,J)
1648             #             -Q THERM(I,J)
1649     5         CONTINUE
1650     C
1651     C         SOLVE THE TRIDIAGONAL SYSTEM
1652             CALL THOMAS
1653     C
1654     C         PLACE THE RESULTS IN TEM3
1655             NEQU=0
1656             DO 6 J=1,NY
1657                 TEM3(I,J)=0.
1658                 K=THMGEO(I,J)
1659                 IF(K.GT.O) TEM3(I,J)=THMTEM(K)
1660                 IF(K.GE.O) GOTO 6
1661                 NEQU=NEQU+1
1662                 TEM3(I,J)=T5(NEQU)
1663     6         CONTINUE
1664     C
1665     4         CONTINUE
1666     C
1667     C         FIND THE MAXIMUM RELATIVE CHANGE IN TEMPERATURE
1668             CALL MAXDIF(2,DELT)
1669     C
1670     C         IF CHANGE LESS THEN TOLERANCE EXIT OUT
1671             IF(DELT.LE.DTEMP) GOTO 7
1672     C
1673     C         CHANGE TOO BIG, CHANGE DTIME
1674             IF(M.GT.5) GOTO 900
1675             DTIME=DTIME*DTEMP/DELT
1676             DTIME=DTIME-DTIME*.01
1677             GOTO 8
1678     C
1679     C         COPY NEW TEMPERATURE TO TEMP
1680     7         CALL COPYR(TEM3,1,TEMP,1,NDX*NDY)

```



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1681 C
1682     RETURN
1683 C
1684 C     ERROR RETURN
1685     900     NERROR=3
1686     RETURN
1687     END
1688 C
1689 C-----
1690 C
1691     SUBROUTINE ENGBAL
1692 C
1693 C     2.9  CALCULATE THE ENERGY BALANCE FOR THE TIMESTEP
1694 C
1695 C     THREE METHODS ARE USED TO CALCULATE THE ENERGY INPUT
1696 C         1. ELECTRICAL POWER * TIME
1697 C         2. HEATING RATE * VOLUME * TIME - HEAT FLOW OUT
1698 C         3. TEMPERATURE RISE * VOLUME * HEAT CAPACITY
1699 C
1700 C     THE LAST TWO METHODS ARE CALCULATED SEPERATELY FOR EACH REGION.
1701 C
1702 C/ INSERT COMGLO
1703 C/ INSERT COMTHM
1704 C/ INSERT COMCON
1705 C/ INSERT COMDIM
1706 C
1707 C     CALCULATE ELECTRICAL ENERGY
1708         DEENG=POWER * DTIME
1709         TEENG=TEENG + DEENG
1710 C
1711 C     CALCULATE HEATING ENERGY AND TEMPERATURE RISE ENERGY
1712         DQENG=0.
1713         TTENG=0.
1714         DO 111 K=1,10
1715     111         TENG(K)=0.
1716         DO 1 J=1,NY
1717             DY=DELTAY(J)
1718             DO 2 I=1,NX
1719                 V=DY*DELTAX(I)*THICK
1720 C
1721 C     CHECK IF BLOCK IN TEMPERATURE DOMAIN
1722         K=THMGEO(I,J)
1723         IF(K.GE.O) GOTO 2
1724 C
1725 C     CALCULATE HEAT PRODUCED MINUS HEAT FLOW OUT TO CONSTANT
1726 C     TEMPERATURE BOUNDARIES.
1727         DQ=QTHERM(I,J)*V*DTIME
1728         IF(I.EQ.NX) GOTO 3
1729         KP=THMGEO(I+1,J)
1730         IF(KP.LE.O) GOTO 3
1731         DQ1=(TEMP(I,J)-THMTEM(KP))*THMCON(K)*DTIME*
1732     #         2.*DY*THICK/DELTAX(I)
1733         DQ=DQ-DQ1
1734     3         IF(I.EQ.1) GOTO 4
1735         KM=THMGEO(I-1,J)
1736         IF(KM.LE.O) GOTO 4
1737         DQ1=(TEMP(I,J)-THMTEM(KM))*THMCON(K)*DTIME*
1738     #         2.*DY*THICK/DELTAX(I)
1739         DQ=DQ-DQ1
1740     4         IF(J.EQ.NY) GOTO 5

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```

1741          KP=THMGEO(I,J+1)
1742          IF(KP.LE.O) GOTO 5
1743          OQ1=(TEMP(I,J)-THMTEM(KP))*THMCON(K)*OTIME*
1744          #          2.*OELTAX(I)*THICK/OY
1745          DQ=OQ-DQ1
1746          5      IF(J.EQ.1) GOTO 6
1747          KM=THMGEO(I,J-1)
1748          IF(KM.LE.O) GOTO 6
1749          DQ1=(TEMP(I,J)-THMTEM(KM))*THMCON(K)*OTIME*
1750          #          2.*OELTAX(I)*THICK/OY
1751          DQ=OQ-DQ1
1752          6      CONTINUE
1753          OQENG=DQENG+OQ
1754          QENG(-K)=QENG(-K)+OQ
1755          C
1756          C      CALCULATE ENERGY INDICATED BY TEMPERATURE RISE.
1757          DT=(TEMP(I,J)-TINIT)*V*THMCAP(-K)
1758          TTENG=TTENG+DT
1759          TENG(-K)=TENG(-K)+OT
1760          C
1761          2      CONTINUE
1762          1      CONTINUE
1763          TQENG=TQENG+OQENG
1764          RETURN
1765          END
1766          C
1767          C-----
1768          C
1769          SUBROUTINE ELECUR
1770          C
1771          C 2.10 FIND THE CURRENT THROUGH A SURFACE PERPENDICULAR TO
1772          C THE X OR Y DIRECTION
1773          C
1774          C IF NIJ=1, THE SURFACE IS PERPENDICULAR TO X, ALONG THE
1775          C GRIOLINE I=NCI.
1776          C OTHERWISE, THE INTEGRAL IS PERPENDICULAR TO Y, ALONG THE
1777          C GRIDLINE J=NCI.
1778          C
1779          C/ INSERT COMGLO
1780          C/ INSERT COMOIM
1781          C/ INSERT COMCON
1782          C
1783          C CHECK ORIENTATION OF INTEGRAL.
1784          IF(NIJ.NE.1) GOTO 10
1785          C
1786          C PERPENDICULAR TO X
1787          H=(OELTAX(NCI)+OELTAX(NCI+1))/2.
1788          HM=(DELTA(X)(NCI)+DELTA(X)(NCI-1))/2.
1789          HS=H**2
1790          HMS=HM**2
1791          CUR=0.
1792          DO 1 J=1,NY
1793          S=ELECON(NCI,J)
1794          E=(HMS*POTENT(NCI+1,J) + (HS-HMS)*POTENT(NCI,J)
1795          #          - HS*POTENT(NCI-1,J))/(H*HM*(H+HM))
1796          CUR=CUR+E*S*OELTAY(J)
1797          1      CONTINUE
1798          CUR=ABS(CUR*THICK)
1799          RETURN
1800          C

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1801 C PERPENDICULAR TO Y
1802 10 H=(DELTAY(NCI)+DELTAY(NCI+1))/2.
1803 HM=(DELTAY(NCI)+DELTAY(NCI-1))/2.
1804 HS=H**2
1805 HMS=HM**2
1806 CUR=0.
1807 DO 2 I=1,NX
1808 S=ELECON(I,NCI)
1809 E=( HMS*POTENT(I,NCI+1) + (HS-HMS)*POTENT(I,NCI)
1810 # - HS*POTENT(I,NCI-1))/(H*HM*(H+HM))
1811 CUR=CUR+E*S*DELTAX(I)
1812 2 CONTINUE
1813 CUR=ABS(CUR*THICK)
1814 RETURN
1815 END
1816 C
1817 C-----
1818 SUBROUTINE OUTPUT(ICODE)
1819 C
1820 C 3.1 CONTROL THE OUTPUT
1821 C
1822 C/ INSERT COMBAS
1823 C/ INSERT COMDIM
1824 C/ INSERT COMGLO
1825 C/ INSERT COMCON
1826 C
1827 C BRANCH TO INITIAL, MIDDLE, AND FINAL OUPUT ROUTINES
1828 GOTO (1,2,3),ICODE
1829 C
1830 C INITIAL OUTPUT
1831 1 IF(NLRES) RETURN
1832 CALL PAGE
1833 C OUTPUT ELECTRICAL GRID STRUCTURE
1834 CALL OUTGRD(1)
1835 CALL PAGE
1836 C OUTPUT THERMAL GRID STRUCTURE
1837 CALL OUTGRD(2)
1838 C IF TAPE STORAGE IS REQUESTED, STORE GRID ETC. ON TAPE
1839 IF(NSTO.LT.200) CALL OUTTAP(1)
1840 RETURN
1841 C
1842 C
1843 C PERIODIC OUTPUT
1844 C CHECK IF PRINTED OUTPUT THIS TIMESTEP
1845 2 IF(MOD(NSTEP,NSPO).NE.0.AND.NSTEP.NE.1) GOTO 5
1846 4 CALL PAGE
1847 CALL OUTI('TIMESTEP NUMBER',NSTEP)
1848 IF(NSTO.LE.200)
1849 # CALL OUTI('CURRENT RECORD NUMBER',NREC)
1850 CALL BLINES(1)
1851 CALL OUTR('TIME AT END OF STEP',TIME)
1852 CALL OUTR('SIZE OF TIMESTEP',DTIME)
1853 CALL BLINES(1)
1854 IF(NTYPE.EQ.4) GOTO 6
1855 CALL OUTI('NO. OF ITERATIONS OF A.D.I.P.',MITER)
1856 CALL OUTR('VOLTAGE BETWEEN ELECTRODES',VOLTS)
1857 CALL OUTR('POWER INPUT TO DOMAIN',POWER)
1858 CALL OUTR('CURRENT BETWEEN ELECTRODES',CUR)
1859 CALL OUTR('RESISTANCE BETWEEN ELECTRODES',RESIST)
1860 CALL BLINES(1)

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1861      6      WRITE(NPRINT,20)
1862      WRITE(NPRINT,22) DEENG,DQENG
1863      WRITE(NPRINT,21) TEENG,TQENG,TTENG
1864      DO 100 K=1,NREG
1865          WRITE(NPRINT,23) K,QENG(K),TENG(K)
1866      100     CONTINUE
1867      CALL BLINES(1)
1868      IF(NTYPE.EQ.4) GOTO 7
1869          CALL OUTINT(4,1)
1870          IF((25+NPY).GT.45) CALL PAGE
1871          CALL OUTINT(5,1)
1872          IF((25+2*NPY).GT.50) CALL PAGE
1873      7       CALL OUTINT(3,1)
1874      C
1875      C      PERIODIC TAPE OUTPUT
1876      5       IF(NSTO.LE.200.AND.(MOD(NSTEP,NSTO).EQ.0.OR.ICODE.EQ.3))
1877          #   CALL OUTTAP(2)
1878      RETURN
1879      C
1880      C
1881      20      FORMAT(4X,'ENERGY BALANCE      ( JOULES )')
1882      21      FORMAT(4X,'CUMULATIVE:  ELECTRICAL ENERGY =',1PE12.4,
1883          #   5X,'HEAT GENERATED =',1PE12.4,5X,
1884          #   'TEMP. RISE ENERGY =',1PE12.4)
1885      22      FORMAT(4X,'TIMESTEP   :  ELECTRICAL ENERGY =',1PE12.4,5X,
1886          #   'HEAT PRODUCED =',1PE12.4)
1887      23      FORMAT(8X,'REGION =',I3,5X,'HEAT GENERATED =',1PE12.4,5X,
1888          #   'TEMP. RISE ENERGY =',1PE12.4)
1889      C
1890      C      FINAL OUTPUT
1891      3       IF(MOD(NSTEP,NSPO).NE.0.AND.NSTEP.NE.1) GOTO 4
1892          IF(MOD(NSTEP,NSTO).NE.0) GOTO 5
1893      RETURN
1894      END
1895      C
1896      C-----
1897      C
1898          SUBROUTINE OUTGRD(ICODE)
1899      C
1900      C      3.2  OUTPUT ONE OF THE GLOBAL VARIABLE ARRAYS
1901      C
1902      C      ICODE INDICATES WHICH ARRAY IS TO BE OUTPUT
1903      C          1 - ELEGE0, THE ELECTRICAL GEOMETRY
1904      C          2 - THMGEO, THE THERMAL GEOMETRY
1905      C          3 - TEMP , THE TEMPERATURE
1906      C          4 - POTENT, THE ELECTRICAL POTENTIAL
1907      C          5 - QTHERM, THE HEATING
1908      C          6 - ELECON, THE ELECTRICAL CONDUCTIVITY
1909      C
1910      C/ INSERT COMBAS
1911      C/ INSERT COMDIM
1912      C/ INSERT COMGLO
1913      C
1914      C      PRINT OUT HEADING
1915          IF(ICODE.EQ.1) WRITE(NPRINT,20)
1916          IF(ICODE.EQ.2) WRITE(NPRINT,21)
1917          IF(ICODE.EQ.3) WRITE(NPRINT,22)
1918          IF(ICODE.EQ.4) WRITE(NPRINT,23)
1919          IF(ICODE.EQ.5) WRITE(NPRINT,24)
1920          IF(ICODE.EQ.6) WRITE(NPRINT,25)

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1921             IF(ICODE.LT.3) GOTO 4
1922 C
1923 C      FORMAT STATEMENTS
1924 20      FORMAT('O',10X,'ELECTRICAL REGIONS OF THE GRID (NOT TO SCALE)')
1925 21      FORMAT('O',10X,'THERMAL REGIONS OF THE GRID (NOT TO SCALE)')
1926 22      FORMAT('O',10X,'TEMPERATURE IN DEGREES CELSIUS')
1927 23      FORMAT('O',10X,'ELECTRICAL POTENTIAL IN VOLTS')
1928 24      FORMAT('O',10X,'HEATING RATE IN JOULES/SECOND-METER**3')
1929 25      FORMAT('O',10X,'ELECTRICAL CONDUCTIVITY IN MHOS/METER')
1930 26      FORMAT('O' COLUMN ' ',10(8X,I2))
1931 27      FORMAT(' ' X ' ',10(3X,F7.3))
1932 28      FORMAT(' ' ROW ' Y ' ')
1933 29      FORMAT(' ',I3,1X,F7.3,10(3X,F7.2))
1934 30      FORMAT(' ',I3,1X,F7.3,10(3X,F7.0))
1935 31      FORMAT(' ',I3,1X,F7.3,10(3X,F7.4))
1936 32      FORMAT('O')
1937 33      FORMAT(' ',I2,5X,50(I2))
1938 34      FORMAT('OCOLUMN ',50(I2))
1939 35      FORMAT('OROW')
1940 C
1941             DO 1 I1=1,NX,10
1942             IT=MINO(I1+9,NX)
1943             DO 2 J2=1,NY,50
1944             JI=MINO(J2+49,NY)
1945 C      PRINT PAGE HEADING
1946             WRITE(NPRINT,26) (I,I=I1,IT)
1947             WRITE(NPRINT,27) (XCOORD(I),I=I1,IT)
1948             WRITE(NPRINT,28)
1949 C      PRINT EACH ROW
1950             DO 3 JM=J2,JI
1951             J=NY+1-JM
1952             IF(ICODE.EQ.3)
1953 #             WRITE(NPRINT,29) J,YCOORD(J),(TEMP(I,J),I=I1,IT)
1954             IF(ICODE.EQ.4)
1955 #             WRITE(NPRINT,29) J,YCOORD(J),(POTENT(I,J),I=I1,IT)
1956             IF(ICODE.EQ.5)
1957 #             WRITE(NPRINT,30) J,YCOORD(J),(QTHERM(I,J),I=I1,IT)
1958             IF(ICODE.EQ.6)
1959 #             WRITE(NPRINT,31) J,YCOORD(J),(ELECON(I,J),I=I1,IT)
1960 3             CONTINUE
1961             WRITE(NPRINT,32)
1962 2             CONTINUE
1963 1             CONTINUE
1964             RETURN
1965 C
1966 C      OUTPUT THE GEOMETRY DEFINING ARRAYS
1967 4             WRITE(NPRINT,35)
1968             DO 5 J=1,NY
1969             JM=NY+1-J
1970             IF(ICODE.EQ.1)
1971 #             WRITE(NPRINT,33) JM,(ELEGEO(I,JM),I=1,NX)
1972             IF(ICODE.EQ.2)
1973 #             WRITE(NPRINT,33) JM,(THMGEO(I,JM),I=1,NX)
1974 5             CONTINUE
1975             WRITE(NPRINT,34) (I,I=1,NX)
1976             RETURN
1977             END
1978 C
1979 C-----
1980 C

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1981      FUNCTION ALINTP(X,Y,Z,Z1,Z2,M,N)
1982      C
1983      C 3.3 INTERPOLATE VALUES FROM GRID
1984      C
1985      C THIS FUNCTION INTERPOLATES A VALUE AT THE POINT (X,Y) FROM
1986      C THE MATRIX Z. THE INTERPOLATION IS LINEAR.
1987      C
1988      DIMENSION Z(50,50),Z1(50),Z2(50)
1989      C
1990      C FIND FIRST X CO-ORDINATE NOT LESS THAN X
1991      C
1992      DO 1 II=2,M
1993      I=II-1
1994      IF(X-Z1(II))3,1,1
1995      C =====
1996      1 CONTINUE
1997      3 XL=X-Z1(I)
1998      XR=Z1(I+1)-X
1999      XBASE=XR+XL
2000      C
2001      C FIND FIRST Y CO-ORDINATE NOT LESS THAN Y
2002      C
2003      DO 2 JJ=2,N
2004      J=JJ-1
2005      IF(Y-Z2(JJ))4,2,2
2006      C =====
2007      2 CONTINUE
2008      4 YL=Y-Z2(J)
2009      YR=Z2(J+1)-Y
2010      YBASE=YR+YL
2011      C
2012      C BILINEAR INTERPOLATION
2013      C
2014      ALINTP=(YL*(XR*Z(I,J+1)+XL*Z(I+1,J+1))
2015      # +YR*(XR*Z(I,J)+XL*Z(I+1,J)))/(XBASE*YBASE)
2016      RETURN
2017      END
2018      C
2019      C-----
2020      C
2021      SUBROUTINE OUTINT(ICODE,IP)
2022      C
2023      C 3.4 INTERPOLATE ONE OF THE GLOBAL VARIABLES
2024      C
2025      C ICODE - DETERMINES WHICH VARIABLE IS INTERPOLATED ( SEE OUTGRD )
2026      C IP = 1, IF PRINTING DESIRED.
2027      C RESULTS OF ITERPOLATION STORED IN TEM3
2028      C
2029      C/ INSERT COMGLO
2030      C/ INSERT COMTEM
2031      C/ INSERT COMDIM
2032      C/ INSERT COMBAS
2033      C/ INSERT COMELE
2034      C/ INSERT COMTHM
2035      C
2036      C
2037      TX=XMAX-XMIN
2038      TY=YMAX-YMIN
2039      SX=TX/(NPX-1.)
2040      SY=TY/(NPY-1.)

```



```

2041 C
2042 C      CDPY APPRDPRIATE ARRAY TO TEM1
2043       IF(ICDDE.EQ.3) CALL COPYR(TEMP,1,TEM1,1,NDX*NDY)
2044       IF(ICDDE.EQ.4) CALL CDPYR(POTENT,1,TEM1,1,NDX*NDY)
2045       IF(ICDDE.EQ.5) CALL COPYR(QTHERM,1,TEM1,1,NDX*NDY)
2046       IF(ICDDE.EQ.6) CALL CDPYR(ELECDN,1,TEM1,1,NDX*NDY)
2047 C
2048 C      DD INTERPDLATIDN
2049 C      RESULTS STDRED IN TEM3, X CDORDINATES IN T1, Y CODRDINATES IN T2
2050 DD 1 J=1,NPY
2051       Y=YMIN+(J-1)*SY
2052       T2(J)=Y
2053       DO 2 I=1,NPX
2054           X=XMIN+(I-1)*SX
2055           T1(I)=X
2056           TEM3(I,J)=ALINTP(X,Y,TEM1,XCDDRD,YCDDRD,NX,NY)
2057       2 CONTINUE
2058       1 CONTINUE
2059 C
2060 C      IF ND PRINTING IS DESIRED, RETURN
2061       IF(IP.NE.1) RETURN
2062 C
2063 C      PRINT OUT ARRAY
2064 C      PRINT OUT HEADING
2065       IF(ICODE.EQ.3) WRITE(NPRINT,22)
2066       IF(ICODE.EQ.4) WRITE(NPRINT,23)
2067       IF(ICODE.EQ.5) WRITE(NPRINT,24)
2068       IF(ICDDE.EQ.6) WRITE(NPRINT,25)
2069 C
2070 C      FDRMAT STATEMENTS
2071       22 FDRMAT('O',10X,'TEMPERATURE IN DEGREES CELSIUS')
2072       23 FDRMAT('O',10X,'ELECTRICAL PDENTIAL IN VDLTS')
2073       24 FDRMAT('O',10X,'HEATING RATE IN JDULES/SECDND-METER**3')
2074       25 FORMAT('O',10X,'ELECTRICAL CDNDUCTIVITY IN MHDS/METER')
2075       26 FDRMAT('O      CDLUMN ',10(8X,I2))
2076       27 FDRMAT('O      X (M)',10(3X,F7.3))
2077       28 FDRMAT('      Y (M)')
2078       29 FDRMAT(' ',F7.3,5X,10(2X,F8.1))
2079 C
2080       DO 6 I1=1,NPX,10
2081           IT=MINO(I1+9,NPX)
2082           DD 7 J2=1,NPY,50
2083               JI=MINO(J2+49,NPY)
2084 C      PRINT PAGE HEADING
2085           WRITE(NPRINT,27) (T1(I),I=I1,IT)
2086           WRITE(NPRINT,28)
2087 C      PRINT EACH RDW
2088           DO 8 JM=J2,JI
2089               J=NPY+1-JM
2090               WRITE(NPRINT,29) T2(J),(TEM3(I,J),I=I1,IT)
2091           8 CONTINUE
2092       7 CONTINUE
2093       6 CONTINUE
2094       RETURN
2095       END
2096 C
2097 C-----
2098 C
2099       SUBROUTINE OUTR(A,B)
2100 C

```



```

2101 C 3.5 OUTPUT A REAL VARIABLE WITH A LABEL
2102 C
2103 C/ INSERT COMBAS
2104 REAL A(8),B
2105 WRITE(NPRINT,20) (A(I),I=1,8),B
2106 20 FORMAT(4X,8A4,' =',1PE12.4)
2107 RETURN
2108 END
2109 C
2110 C-----
2111 C
2112 SUBROUTINE OUTI(A,B)
2113 C
2114 C 3.6 OUTPUT A LABEL AND AN INTEGER VARIABLE
2115 C
2116 C/ INSERT COMBAS
2117 REAL A(8)
2118 INTEGER B
2119 WRITE(NPRINT,20) (A(I),I=1,8),B
2120 20 FORMAT(4X,8A4,' =',I12)
2121 RETURN
2122 END
2123 C
2124 C-----
2125 C
2126 SUBROUTINE OUTH(A,B)
2127 C
2128 C 3.7 OUTPUT A LABEL AND A HOLLERITH VARIABLE.
2129 C
2130 C/ INSERT COMBAS
2131 REAL A(8)
2132 REAL B
2133 WRITE(NPRINT,20) (A(I),I=1,8),B
2134 20 FORMAT(4X,8A4,' =',8X,A4)
2135 RETURN
2136 END
2137 C
2138 C-----
2139 C
2140 SUBROUTINE OUTTAP(ICODE)
2141 C
2142 C 3.8 OUTPUT RUN INFORMATION TO MAGNETIC TAPE
2143 C
2144 C/ INSERT COMBAS
2145 C/ INSERT COMGLO
2146 C/ INSERT COMELE
2147 C/ INSERT COMTHM
2148 C/ INSERT COMCON
2149 C/ INSERT COMDIM
2150 C
2151 GOTO (1,2) , ICODE
2152 C
2153 C INITIAL STORAGE
2154 1 WRITE(NONLIN) ELEGED,THMGEO,DELTAX,DELTAY,THICK,
2155 # XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,ELEVOL,
2156 # ELEALP,ELEBET,EPSELE,THMCON,THMCAP,THMTEM,
2157 # TINIT,NX,NY,NALPHA,MMAX,NREG,NGEO,NSPO,
2158 # NSTO,NPX,NPY,NIJ,NCI
2159 NREC=NREC+1
2160 RETURN

```



```

2161 C
2162 C PERIODIC STORAGE
2163 2 WRITE(NONLIN) NSTEP, TIME, POTENT, QTHERM, TEMP, TEENG, TENG,
2164 # TQENG, QENG, NREC, OTIME
2165 NREC=NREC+1
2166 RETURN
2167 END
2168 C
2169 C-----
2170 C
2171 SUBROUTINE TESENO
2172 C
2173 C 4.1 TEST FOR COMPLETION OF RUN
2174 C
2175 C/ INSERT COMBAS
2176 C/ INSERT COMGLO
2177 C/ INSERT COMCON
2178 C/ INSERT COMOIM
2179 C
2180 IF(NERROR.NE.O) CALL ENORUN
2181 IF(NSTEP.GE.NRUN) NLENO = .TRUE.
2182 IF(TIME.GE.(HTIME+CTIME)) NLEND = .TRUE.
2183 RETURN
2184 END
2185 C
2186 C-----
2187 C
2188 SUBROUTINE ENDRUN
2189 C
2190 C 4.2 TERMINATE THE RUN
2191 C
2192 C/ INSERT COMBAS
2193 C/ INSERT COMOOP
2194 C/ INSERT COMOIM
2195 C
2196 C CHECK IF A NORMAL TERMINATION
2197 IF(.NOT.NLEND) GO TO 100
2198 CALL BLINES(2)
2199 CALLMESSAGE(48H 4.2 TERMINATE THE RUN )
2200 WRITE(18,20)
2201 20 FORMAT('+',50X,'*** NORMAL EXIT')
2202 CALL BLINES(2)
2203 CALL DAYTIM
2204 CALL RUNTIM
2205 CALL PAGE
2206 STOP
2207 C
2208 C ERROR WAS FOUND SOMEWHERE, ABNORMAL TERMINATION
2209 100 CONTINUE
2210 CALL BLINES(3)
2211 CALLMESSAGE(48H 4.2 ABNORMAL EXIT )
2212 IF(NERROR.EQ.1)
2213 # CALLMESSAGE(48H *** SOLUTION FAILED TO CONVERGE IN ELEPOT )
2214 IF(NERROR.EQ.2)
2215 # CALLMESSAGE(48H *** GEOMETRIC ERROR DETECTED IN ROUTINE QCALC)
2216 IF(NERROR.EQ.3)
2217 # CALLMESSAGE(48H *** ERROR RETURN FROM ROUTINE TCALC )
2218 IF(NERROR.EQ.4)
2219 # CALLMESSAGE(48H *** ERROR RETURN FROM SUBROUTINE ELECOF )
2220 CALL OUTGRO(4)

```



```

2221          CALL OUTGRD(5)
2222          CALL OUTGRD(3)
2223      C
2224      C      PRINT THE FINAL TIMES
2225          CALL BLINES(2)
2226          CALL DAYTIM
2227          CALL RUNTIM
2228          CALL PAGE
2229      C
2230          STOP 2230
2231          END
2232      C
2233      C-----
2234      C
2235          SUBROUTINE MESSAGE(KMESS)
2236      C
2237      C U.1  PRINT 48-CHARACTER MESSAGE ON OUTPUT CHANNEL
2238      C
2239      C      VERSION 1B          17/12/73          KVR/MHH          CULHAM
2240      C
2241      C/ INSERT COMBAS
2242          DIMENSION KMESS(12)
2243      C
2244          WRITE(NOUT,9900) (KMESS(J),J=1,12)
2245      C
2246          RETURN
2247      9900  FORMAT(4X,12A4)
2248          END
2249      C
2250      C-----
2251      C
2252          SUBROUTINE PAGE
2253      C
2254      C U.2  FETCH NEW PAGE ON OUTPUT CHANNEL
2255      C
2256      C      VERSION 1B          17/12/73          KVR/MHH          CULHAM
2257      C
2258      C/ INSERT COMBAS
2259          WRITE(NOUT,9900)
2260      C
2261          RETURN
2262      9900  FORMAT(1H1)
2263          END
2264      C
2265      C-----
2266      C
2267          SUBROUTINE BLINES(K)
2268      C
2269      C U.3  INSERT BLANK LINES ON OUTPUT CHANNEL
2270      C
2271      C      VERSION 1B          17/12/73          KVR/MHH          CULHAM
2272      C
2273      C/ INSERT COMBAS
2274      C
2275          DO 100 J=1,K
2276      100  WRITE(NOUT,9900)
2277      C
2278          RETURN
2279      9900  FORMAT(1H )
2280          END

```



```

2281 C
2282 C-----
2283 C
2284 SUBROUTINE RUNTIM
2285 C
2286 C U.12 UPDATE CPU TIME (MINS) AND PRINT IT
2287 C
2288 C VERSION 2B 17/12/73 KVR/MHH CULHAM
2289 C
2290 C/ INSERT COMBAS
2291 C
2292 C TIME(1,O,ICPUT) IS A MTS LIBRARY FUNCTION GIVING THE CPU-TIME
2293 C USED SO FAR (ICPUT IN MSEC)
2294 C CALL TIME(1,O,ICPUT)
2295 C ISEC = ICPUT/1000
2296 C MIN = ISEC/60
2297 C ISEC = ISEC - 60*MIN
2298 C SEC = ISEC
2299 C CPTIME = MIN + SEC/60.
2300 C WRITE(NOUT,9900) MIN,ISEC
2301 C
2302 C RETURN
2303 9900 FORMAT(5X,22HCPU TIME USED SO FAR =,I4,5H MINS,I4,5H SECS)
2304 C END
2305 C
2306 C-----
2307 C
2308 SUBROUTINE DAYTIM
2309 C
2310 C U.13 PRINT DATE AND TIME
2311 C
2312 C VERSION 2B 17/12/73 KVR/MHH CULHAM
2313 C
2314 C/ INSERT COMBAS
2315 C TIME IS AN MTS LIBRARY ROUTINE WHICH RETURNS THE DATE AND TIME
2316 C DIMENSION DATE(4),TIIME(2)
2317 C CALL TIME(21,O,DATE)
2318 C CALL TIME(4,O,TIIME)
2319 C
2320 C WRITE(NOUT,9900) DATE,TIIME
2321 C RETURN
2322 9900 FORMAT(5X,4A4,5X,2A4)
2323 C END
2324 C
2325 C-----
2326 C
2327 SUBROUTINE RESETR(PA,KDIM,PVALUE)
2328 C
2329 C U.14 RESET REAL ARRAY TO SPECIFIED VALUE
2330 C
2331 C VERSION 1B 17/12/73 KVR/MHH CULHAM
2332 C
2333 C DIMENSION PA(KDIM)
2334 C
2335 C DO 100 J=1,KDIM
2336 C PA(J) = PVALUE
2337 100 CONTINUE
2338 C
2339 C RETURN
2340 C END

```



```

2341 C
2342 C-----
2343 C
2344 C      SUBROUTINE RESETI(KA,KDIM,KVALUE)
2345 C
2346 C U.15 RESET INTEGER ARRAY TO SPECIFIED VALUE
2347 C
2348 C      VERSION 1B      17/12/73      KVR/MHH      CULHAM
2349 C
2350 C      DIMENSION KA(KDIM)
2351 C      DO 100 J=1,KDIM
2352 C      KA(J) = KVALUE
2353 C      100 CONTINUE
2354 C
2355 C      RETURN
2356 C      END
2357 C
2358 C-----
2359 C
2360 C      SUBROUTINE RESETH(KA,KDIM,KVALUE)
2361 C
2362 C U.16 RESET HOLLERITH ARRAY TO SPECIFIED VALUE
2363 C
2364 C      VERSION 1B      17/12/73      KVR/MHH      CULHAM
2365 C
2366 C      DIMENSION KA(KDIM), KVALUE(1)
2367 C
2368 C      DO 100 J=1,KDIM
2369 C      KA(J) = KVALUE(1)
2370 C      100 CONTINUE
2371 C
2372 C      RETURN
2373 C      END
2374 C
2375 C-----
2376 C
2377 C      SUBROUTINE JOBTIM(PTIME)
2378 C
2379 C U.17 FETCH ALLOCATED JOBTIME (MINS)
2380 C
2381 C      VERSION 2B      17/12/73      KVR/MHH      CULHAM
2382 C
2383 C      SET CPU TIME COUNTER TO O.
2384 C      CALL TIME(O,O,JUNK)
2385 C
2386 C      GUINFO(78,INFO1) IS AN MTS LIBRARY FUNCTION WHICH GIVES THE GLOBAL
2387 C      TIME REMAINING
2388 C      GUINFO(86,INFO2) IS AN MTS LIBRARY FUNCTION WHICH GIVES THE LOCAL
2389 C      TIME REMAINING
2390 C      INFO1 AND INFO2 ARE IN CPU TIME UNITS. ONE TIME UNIT
2391 C      EQUALS 13.020833333 MICROSECS. CPTIME IS IN MINS.
2392 C      CALL GUINFO(78,INFO1)
2393 C      CALL GUINFO(86,INFO2)
2394 C      INFO = MINO(INFO1,INFO2)
2395 C      PTIME = 2.1701389*INFO
2396 C
2397 C      RETURN
2398 C      END
2399 C
2400 C-----

```



```

2401 C
2402 SUBROUTINE RESETL(KLA,KDIM,KLVAL)
2403 C
2404 C U.19 RESET LOGICAL ARRAY TO SPECIFIED VALUE
2405 C
2406 C VERSION 1B 17/12/73 KVR/MHH CULHAM
2407 C
2408 LOGICAL KLA, KLVAL
2409 DIMENSION KLA(KDIM)
2410 DO 100 J=1,KDIM
2411 KLA(J) = KLVAL
2412 100 CONTINUE
2413 C
2414 RETURN
2415 END
2416 C
2417 C-----
2418 C
2419 SUBROUTINE SCALER(PA,KDIM,PC)
2420 C
2421 C U.21 SCALE A REAL ARRAY BY A REAL VALUE
2422 C
2423 C VERSION 1B 17/12/73 KVR/MHH CULHAM
2424 C
2425 DIMENSION PA(KDIM)
2426 C
2427 DO 100 J=1,KDIM
2428 PA(J) = PA(J) * PC
2429 100 CONTINUE
2430 C
2431 RETURN
2432 END
2433 C
2434 C-----
2435 C
2436 SUBROUTINE COPYR(PA1,K1,PA2,K2,KDIM)
2437 C
2438 C U.23 COPY ONE REAL ARRAY INTO ANOTHER
2439 C
2440 C VERSION 1B 17/12/73 KVR/MHH CULHAM
2441 C
2442 DIMENSION PA1(KDIM),PA2(KDIM)
2443 C
2444 DO 100 J=1,KDIM
2445 I1 = K1 + J - 1
2446 I2 = K2 + J - 1
2447 PA2(I2) = PA1(I1)
2448 100 CONTINUE
2449 C
2450 RETURN
2451 END
END OF FILE
1 C/ MODULE COMBAS
2 C
3 C 1.1 BASIC SYSTEM PARAMETERS
4 COMMON /COMBAS/
5 R ALTIME, CPTIME, STIME,
6 I LABEL1, LABEL2, LABEL3, LABEL4,
7 I LABEL5, LABEL6, LABEL7, LABEL8,
8 I NDIARY, NIN, NLEDGE, NONLIN,

```



```

9      I      NOUT,      NPRINT,      NPUNCH,      NREAD,
10     I      NREC,      NRESUM,      NRUN,      NSTEP,
11     L      NLEND,      NLRES
12 C
13     LOGICAL NLEND,NLRES
14 C
15     INTEGER*4 LABEL1(12),LABEL2(12),LABEL3(12),LABEL4(12),
16     I      LABEL5(12),LABEL6(12),LABEL7(12),LABEL8(12)
17 C/ MODULE COMODP
18 C
19 C 1.9      DEVELOPMENT AND DIAGNOSTIC PARAMETERS
20     COMMON /COMDDP/
21     I      MAXDUM,      MXDUMP,      NADUMP,      NCLASS,
22     I      NPOUMP,      NPOINT,      NSUB,      NVOUMP,
23     L      NLCHED,      NLHEAD,      NLOMT1,      NLOMT2,
24     L      NLOMT3,      NLREPT
25 C
26     LOGICAL NLCHED,NLHEAD(9),NLOMT1(50),NLOMT2(50),NLOMT3(50),
27     L      NLREPT
28 C
29     INTEGER*4 NADUMP(20),NPOUMP(20),NVOUMP(20)
30 C/ MODULE COMGLO
31 C
32 C 1.2 GLOBAL VARIABLES
33     COMMON /COMGLO/
34     #      ELECON,QTHERM,POTENT,TEMP,
35     #      DELTAX,DELTAY,THICK,OTIME,TIME,
36     #      XCOORD,YCOORD,XMIN,XMAX,YMIN,YMAX,
37     #      ELEGED,THMGEO
38 C
39     REAL ELECON(50,50),QTHERM(50,50),DELTAX(50),
40     #      POTENT(50,50),TEMP(50,50),DELTAY(50),
41     #      XCOORD(50),YCOORD(50)
42     INTEGER*4 ELEGED(50,50),THMGEO(50,50)
43 C/ MODULE COMELE
44 C
45 C 1.3 ELECTRICAL CONDUCTIVITY AND DIFFERENCE EQU. COEFFICENTS
46     COMMON /COMELE/
47     #      ECXP,ECXM,ECYP,ECYM,ERHS,EXMXP,EYMYP,
48     #      ELEVOL,ELEALP,ELEBET,ELEPAR,EPSELE
49 C
50     REAL ECXP(50,50),ECXM(50,50),ECYP(50,50),ECYM(50,50),
51     #      ELEVOL(10),ELEALP(10),ELEBET(10),ELEPAR(50),
52     #      ERHS(50,50),EXMXP(50,50),EYMYP(50,50)
53 C/ MODULE COMTHM
54 C
55 C 1.4 THERMAL CONDUCTIVITY AND HEAT CAPACITY
56     COMMON /COMTHM/
57     #      THMCON,THMCAP,THMTEM,TCXP,TCXM,TCYP,TCYM,
58     #      TCX,TCY,TCRHS
59 C
60     REAL THMCON(10),THMCAP(10),THMTEM(10)
61     REAL TCXP(50,50),TCXM(50,50),TCYP(50,50),TCYM(50,50)
62     REAL TCX(50,50),TCY(50,50),TCRHS(50,50)
63 C/ MODULE COMTEM
64 C
65 C 1.5 TEMPERARY ARRAYS
66     COMMON /COMTEM/
67     #      TEM1,TEM2,TEM3,T1,T2,T3,T4,T5
68 C

```



```

69          REAL TEM1(50,50),TEM2(50,50),TEM3(50,50),T1(50),
70          #          T2(50),T3(50),T4(50),T5(50)
71      C/  MODULE COMDIM
72      C
73      C  1.6  DIMENSION AND COUNTER VARIABLES
74          COMMON /COMDIM/
75          #          NX,NY,NEQU,NALPHA,MITER,MMAX,NREG,NGEO,NERROR,NTYPE,
76          #          NSPO,NPX,NPY,NIJ,NCI,NDX,NDY,NSTO
77      C
78          INTEGER*4 NX,NY,NDX,NDY,NEQU,NALPHA,MITER,MMAX
79          INTEGER*4 NREG,NGEO,NERROR,NTYPE,NSPO,NPX,NPY
80          INTEGER*4 NIJ,NCI,NSTO
81      C/  MODULE COMCON
82      C
83      C  1.7  CONTROL THE HEATING
84          COMMON /COMCON/
85          #          HTIME,CTIME,CCUR,CPOW,DTEMP,DELT,CUR,
86          #          VOLTS,RESIST,POWER,CVOL,TINIT,DEENG,TEENG,
87          #          DQENG,QENG,TQENG,TTENG,TENG,SCALE
88      C
89          REAL QENG(10),TENG(10)

```

END OF FILE

Appendix II - Sample Output from MEGAERA

```

1  &INMOD NRUN=100 &END
2  &LABELS
3    LABEL1='MEGAERA RUN NO. 35      PARALLEL ELECTRODES',
4    LABEL2='OVERBURDEN CONDUCTIVITY RATIO  OS/OB = 1.0',
5    LABEL4='GEOMETRY SET UP AND ENTERED BY ALLAN HIEBERT',
6  &END
7  &INPUT1      NX=50,NY=50,
8    DELTAX=50*1.5,DELTAY=8*5.0,2.5,3*2.0,1.5,25*1.2,
9    1.5,3*2.0,2.5,6*5.0,10.0,NREG=5,
10 &END
11 &REGION  MINI=1,MAXI=50,MINJ=14,MAXJ=38,
12   ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.E-3,
13   TTYPE='COND',THMRC=1.6E6,THMK=1.8,
14 &END
15 &REGION  MINI=1,MAXI=50,MINJ=1,MAXJ=13,
16   ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.OE-3,
17   TTYPE='COND',THMRC=1.6E6,THMK=1.8,
18 &END
19 &REGION  MINI=1,MAXI=50,MINJ=39,MAXJ=50,
20   ETYPE='DOMA',EALPHA=2.29E-2,EBETA=1.OE-3,
21   TTYPE='COND',THMRC=1.6E6,THMK=1.8,
22 &END
23 &REGION  MINI=1,MAXI=1,MINJ=24,MAXJ=29,
24   ETYPE='ELEC',VOLTS=1000.,
25   TTYPE='COND',THMRC=1.E6,THMK=3.0,
26 &END
27 &REGION  MINI=50,MAXI=50,MINJ=24,MAXJ=29,
28   ETYPE='ELEC',VOLTS=0.,
29   TTYPE='COND',THMRC=1.E6,THMK=3.0,
30 &END
31 &INPUT2
32   NSPO=10,XMIN=1.0,XMAX=49.0,NPX=17,
33   YMIN=40,YMAX=85,NPY=10,
34 &END
35 &INPUT3
36   TINIT=15.,DTIME=1.E5,HTIME=3.154E7,NTYPE=3,
37   CP0W=12.E3,CVOL=1000.,DTEMP=.05,NCI=20,
38   MMAX=350,EPSELE=.02,
39 &END
40 &INPLOT
41   LABEL1='PARALLEL PLATE RUN NO. 35      80/11/25',NLAB1=38,
42   LABEL2='CONDUCTIVITY RATIO  OB/OS = 1.0/ 1.0',NLAB2=38,
43   NCPLTS=1,CPTIME=3.15E7,NCCODE=3,
44   CXMIN=1.0,CXMAX=74.0,CYMIN=30.,CYMAX=100.,
45   NPPLTS=1,PPTIME=3.15E7,NPCODE=7,
46   PXMIN=1.0,PXMAX=99.0,PYMIN=15.,PYMAX=115.,
47 &END

```


P R O G R A M M E G A E R A

ADH AUGUST, 1980

MEGAERA RUN NO. 35 PARALLEL ELECTRODES
OVERBURDEN CONDUCTIVITY RATIO OS/OB = 1.0

GEOMETRY SET UP AND ENTERED BY ALLAN HIEBERT

THICKNESS OF 2D SLICE (IHICK) = 1.0000E+00
GEOMETRY OF PROBLEM = VERT
NUMBER OF REGIONS (NREG) = 5

REGION NUMBER = 1
ELECTRICAL TYPE = DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY = 2.2900E-02
CONDUCTIVITY AT 24 CELSIUS = 1.0000E-03
THERMAL REGION TYPE = COND
THERMAL CONDUCTIVITY = 1.8000E+00
THERMAL HEAT CAPACITY = 1.6000E+06

REGION NUMBER = 2
ELECTRICAL TYPE = DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY = 2.2900E-02
CONDUCTIVITY AT 24 CELSIUS = 1.0000E-03
THERMAL REGION TYPE = COND
THERMAL CONDUCTIVITY = 1.8000E+00
THERMAL HEAT CAPACITY = 1.6000E+06

REGION NUMBER = 3
ELECTRICAL TYPE = DOMA
TEMP. DEPENDENCE OF CONDUCTIVITY = 2.2900E-02
CONDUCTIVITY AT 24 CELSIUS = 1.0000E-03
THERMAL REGION TYPE = COND
THERMAL CONDUCTIVITY = 1.8000E+00
THERMAL HEAT CAPACITY = 1.6000E+06

REGION NUMBER = 4
ELECTRICAL TYPE = ELEC
VOLTAGE (BEFORE SCALING) = 1.0000E+03
THERMAL REGION TYPE = COND
THERMAL CONDUCTIVITY = 3.0000E+00
THERMAL HEAT CAPACITY = 1.0000E+06

REGION NUMBER = 5
ELECTRICAL TYPE = ELEC
VOLTAGE (BEFORE SCALING) = 0.0

THERMAL REGION TYPE = CONO
THERMAL CONDUCTIVITY = 3.0000E+00
THERMAL HEAT CAPACITY = 1.0000E+06

NO. OF STEPS PER PRINTED OUTPUT = 10
NO. OF STEPS PER TAPE STORAGE = 1000
NO. OF INTERPOLATION POINTS IN X = 17
NO. OF INTERPOLATION POINTS IN Y = 10
X MINIMUM FOR INTERPOLATION = 1.0000E+00
X MAXIMUM FOR INTERPOLATION = 4.9000E+01
Y MINIMUM FOR INTERPOLATION = 4.0000E+01
Y MAXIMUM FOR INTERPOLATION = 8.5000E+01

INITIAL TEMPERATURE IN CELSIUS = 1.5000E+01
TOTAL HEATING TIME IN SECONDS = 3.1540E+07
INITIAL TIMESTEP SIZE IN SECONDS = 1.0000E+05
GRIDLINE FOR CURRENT INTEGRAL = 20
CONSTANT POWER (WATTS) = 1.2000E+04
CHANGE IN TEMPERATURE / TIMESTEP = 5.0000E-02
MAXIMUM NO. OF ITERATIONS (MMAX) = 350
ELECTRICAL CONVERGENCE CRITERIA = 2.0000E-02
NUMBER OF ITERATION PARAMETERS = 50

TIMESTEP NUMBER = 1

TIME AT END OF STEP = 1.3055E+04

SIZE OF TIMESTEP = 1.3055E+04

NO. OF ITERATIONS OF A.D.I.P. = 226

VOLTAGE BETWEEN ELECTRODES = 5.2318E+03

POWER INPUT TO DOMAIN = 1.2000E+04

CURRENT BETWEEN ELECTRODES = 2.2937E+00

RESISTANCE BETWEEN ELECTRODES = 2.2810E+03

ENERGY BALANCE (JOULES)

TIMESTEP : ELECTRICAL ENERGY = 1.5666E+08

CUMULATIVE: ELECTRICAL ENERGY = 1.5666E+08

HEAT PRODUCED = 1.5809E+08

HEAT GENERATED = 1.5809E+08

TEMP. RISE ENERGY = 1.5801E+08

REGION = 1

HEAT GENERATED = 1.2496E+08

TEMP. RISE ENERGY = 1.2484E+08

REGION = 2

HEAT GENERATED = 1.5665E+07

TEMP. RISE ENERGY = 1.5634E+07

REGION = 3

HEAT GENERATED = 1.7467E+07

TEMP. RISE ENERGY = 1.7437E+07

REGION = 4

HEAT GENERATED = 0.0

TEMP. RISE ENERGY = 4.8345E+04

REGION = 5

HEAT GENERATED = 0.0

TEMP. RISE ENERGY = 5.4437E+04

ELECTRICAL POTENTIAL IN VOLTS

Y (M)	X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	3578.0	3557.6	3515.4	3515.4	3456.1	3384.8	3305.7	3222.0	3135.6	3047.9	2959.6
80.000	3826.4	3790.1	3719.3	3719.3	3627.0	3524.0	3417.0	3309.5	3203.2	3098.7	2995.9
75.000	4207.6	4121.0	3979.5	3979.5	3824.1	3671.7	3527.6	3392.3	3264.8	3143.7	3027.5
70.000	4963.0	4578.8	4259.0	4259.0	4004.3	3793.2	3612.3	3452.6	3308.2	3174.7	3048.9
65.000	5207.7	4780.2	4370.0	4370.0	4069.4	3834.3	3639.6	3471.6	3321.6	3184.2	3055.5
60.000	4709.5	4463.1	4197.7	4197.7	3967.5	3769.5	3596.3	3441.6	3300.5	3169.4	3045.5
55.000	4097.4	4030.0	3912.3	3912.3	3775.8	3637.1	3502.5	3374.1	3251.8	3134.6	3021.6
50.000	3757.9	3726.9	3665.3	3665.3	3583.1	3489.3	3390.0	3288.9	3187.9	3087.7	2988.7
45.000	3529.8	3511.6	3473.7	3473.7	3419.8	3354.3	3280.8	3202.1	3120.4	3036.9	2952.3
40.000	3365.9	3353.7	3327.6	3327.6	3289.4	3241.2	3185.3	3123.5	3057.4	2988.2	2917.0

Y (M)	X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
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85.000	2871.1	2782.4	2693.5	2604.4	2514.9	2425.0	2334.9	2242.2
80.000	2894.6	2794.1	2694.1	2593.7	2492.6	2390.0	2285.5	2182.8
75.000	2914.8	2804.3	2694.7	2584.9	2473.7	2359.9	2242.2	2122.8
70.000	2928.4	2811.1	2695.2	2579.2	2461.3	2339.8	2212.8	2084.4
65.000	2932.6	2813.3	2695.6	2577.8	2457.9	2334.2	2204.4	2074.3
60.000	2926.5	2810.5	2695.9	2581.1	2464.5	2344.5	2219.3	2094.3
55.000	2911.5	2803.4	2696.0	2588.5	2479.6	2368.4	2253.8	2134.8
50.000	2890.6	2793.2	2696.1	2598.6	2500.5	2401.2	2300.3	2194.3
45.000	2867.2	2781.8	2696.1	2610.2	2524.0	2437.6	2351.3	2264.3
40.000	2844.3	2770.6	2696.4	2621.9	2547.6	2473.7	2400.7	2327.7

HEATING RATE IN JOULES/SECOND-METER**3

Y (M)	X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	1.4	1.3	1.3	1.3	1.1	1.0	1.0	0.9	0.8	0.8	0.7
80.000	3.0	2.7	2.3	2.0	2.0	1.7	1.4	1.3	1.1	1.0	1.0
75.000	8.2	6.4	4.6	3.4	2.6	2.6	2.1	1.7	1.5	1.3	1.2
70.000	67.1	18.3	8.9	5.3	3.6	3.6	2.6	2.1	1.7	1.5	1.3
65.000	4.7	20.9	10.8	6.2	4.0	4.0	2.9	2.2	1.8	1.6	1.4
60.000	32.4	14.1	7.8	4.9	3.4	3.4	2.5	2.0	1.7	1.4	1.3

55.000	6.1	5.1	3.9	3.0	2.3	1.9	1.6	1.4	1.2	1.1
50.000	2.4	2.3	2.0	1.7	1.5	1.3	1.1	1.0	1.0	0.9
45.000	1.2	1.2	1.1	1.0	0.9	0.9	0.8	0.7	0.7	0.7
40.000	0.7	0.7	0.6	0.6	0.6	0.6	0.5	0.5	0.5	0.5
Y (M)	X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000		
85.000	0.7	0.7	0.7	0.7	0.7	0.7	0.8	0.8		
80.000	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.1		
75.000	1.1	1.1	1.1	1.1	1.1	1.1	1.2	1.3		
70.000	1.2	1.2	1.2	1.2	1.3	1.4	1.4	1.5		
65.000	1.3	1.2	1.2	1.2	1.3	1.4	1.4	1.6		
60.000	1.2	1.2	1.2	1.2	1.2	1.3	1.3	1.5		
55.000	1.1	1.0	1.0	1.0	1.1	1.1	1.1	1.3		
50.000	0.9	0.8	0.8	0.8	0.9	0.9	0.9	1.0		
45.000	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7		
40.000	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5		

TEMPERATURE IN DEGREES CELSIUS

Y (M)	X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
80.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
75.000	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
70.000	15.5	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
65.000	15.0	15.2	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0
60.000	15.3	15.1	15.1	15.1	15.0	15.0	15.0	15.0	15.0	15.0	15.0
55.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
50.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
45.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
40.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0
Y (M)	X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000			
85.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
80.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
75.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	5.0			
70.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
65.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
60.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
55.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
50.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
45.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			
40.000	15.0	15.0	15.0	15.0	15.0	15.0	15.0	15.0			

TIMESTEP NUMBER = 79
TIME AT END OF STEP = 3.1540E+07
SIZE OF TIMESTEP = 1.5970E+06
NO. OF ITERATIONS OF A.D.I.P. = 18
VOLTAGE BETWEEN ELECTRODES = 3.0009E+03
POWER INPUT TO DOMAIN = 1.2000E+04
CURRENT BETWEEN ELECTRODES = 3.9988E+00
RESISTANCE BETWEEN ELECTRODES = 7.5046E+02

ENERGY BALANCE (JOULES)
TIMESTEP : ELECTRICAL ENERGY = 1.9164E+10 HEAT PRODUCTION = 1.9173E+10
CUMULATIVE : ELECTRICAL ENERGY = 3.7848E+11 HEAT GENERATION = 3.7824E+11
REGION = 1 HEAT GENERATED = 2.6882E+11 TEMP. RISE ENERGY = 2.5076E+11 TEMP. RISE ENERGY = 3.7819E+11
REGION = 2 HEAT GENERATED = 5.1464E+10 TEMP. RISE ENERGY = 5.8573E+10
REGION = 3 HEAT GENERATED = 5.6879E+10 TEMP. RISE ENERGY = 6.4705E+10
REGION = 4 HEAT GENERATED = 0.0 TEMP. RISE ENERGY = 2.0873E+09
REGION = 5 HEAT GENERATED = 0.0 TEMP. RISE ENERGY = 2.0876E+09

ELECTRICAL POTENTIAL IN VOLTS

Y (M)	X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000		2382.3	2366.1	2331.8	2281.9	2219.3	2146.9	2067.1	1981.8	1892.6	1800.7
80.000		2529.3	2506.8	2460.7	2396.4	2318.7	2231.4	2137.6	2039.1	1937.7	1834.2
75.000		2695.4	2657.6	2589.3	2503.8	2407.7	2304.7	2197.2	2086.8	1974.7	1861.5
70.000		2927.9	2812.6	2697.5	2584.5	2470.4	2354.5	2236.8	2117.9	1998.6	1879.0
65.000		2994.1	2870.4	2734.4	2610.3	2489.8	2369.4	2248.5	2127.1	2005.5	1884.1
60.000		2857.1	2777.0	2675.5	2569.0	2458.7	2345.3	2229.5	2112.3	1994.2	1875.8
55.000		2652.4	2620.0	2558.8	2479.2	2387.8	2288.6	2184.3	2076.5	1966.7	1855.6
50.000		2491.9	2471.4	2428.8	2368.5	2294.8	2211.3	2121.0	2025.7	1927.2	1826.4
45.000		2347.9	2332.7	2300.6	2253.6	2194.3	2125.3	2048.9	1966.9	1880.8	1791.9
40.000		2218.9	2207.2	2182.1	2144.7	2096.8	2040.1	1976.2	1906.7	1832.9	1755.8

Y (M)	X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000
85.000		1706.9	1612.0	1516.4	1420.8	1325.6	1231.3	1138.7
80.000		1729.4	1624.0	1518.1	1412.2	1306.6	1201.5	1097.6
75.000		1747.7	1633.7	1519.5	1405.3	1291.2	1177.3	1063.9
70.000		1759.4	1639.8	1520.4	1400.9	1281.4	1161.8	1042.2
65.000		1762.7	1641.6	1520.6	1399.6	1278.5	1157.3	1035.9
60.000		1757.3	1638.7	1520.2	1401.7	1283.1	1164.6	1046.1
55.000		1743.8	1631.6	1519.2	1406.8	1294.5	1182.5	1071.1
50.000		1724.2	1621.2	1517.7	1414.2	1310.9	1208.4	1107.1
45.000		1700.9	1608.8	1516.0	1423.0	1330.6	1239.2	1149.5
40.000		1676.5	1595.7	1514.1	1432.4	1351.3	1271.4	1193.5

HEATING RATE IN JOULES/SECOND-METER**3

Y (M)	X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
85.000		1.3	1.3	1.3	1.3	1.4	1.4	1.4	1.4	1.4	1.3
80.000		2.3	2.2	2.2	2.1	2.1	2.1	2.0	2.0	1.9	1.9
75.000		5.0	4.3	3.8	3.4	3.1	2.9	2.8	2.6	2.5	2.5
70.000		32.9	10.4	6.4	5.0	4.2	3.8	3.4	3.2	3.0	2.9
65.000		2.4	11.6	7.5	5.6	4.6	4.1	3.7	3.4	3.2	3.0
60.000		16.4	8.3	5.8	4.6	4.0	3.6	3.3	3.1	2.9	2.8

55.000	4.0	3.6	3.3	3.1	2.9	2.7	2.6	2.5	2.4	2.3
50.000	2.0	1.9	1.9	1.9	1.9	1.9	1.8	1.8	1.8	1.7
45.000	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
40.000	0.7	0.7	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8

X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000			
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Y (M)

85.000	1.3	1.3	1.3	1.3	1.3	1.3	1.4			
80.000	1.9	1.8	1.8	1.8	1.8	1.9	1.9			
75.000	2.4	2.4	2.3	2.3	2.4	2.4	2.5			
70.000	2.8	2.8	2.7	2.7	2.8	2.9	3.0			
65.000	2.9	2.9	2.9	2.9	2.9	3.0	3.1			
60.000	2.7	2.7	2.7	2.7	2.7	2.8	2.9			
55.000	2.3	2.2	2.2	2.2	2.3	2.3	2.4			
50.000	1.7	1.7	1.7	1.7	1.7	1.7	1.8			
45.000	1.2	1.2	1.2	1.2	1.2	1.2	1.2			
40.000	0.9	0.9	0.9	0.9	0.9	0.9	0.8			

TEMPERATURE IN DEGREES CELSIUS

X (M)	1.000	4.000	7.000	10.000	13.000	16.000	19.000	22.000	25.000	28.000
Y (M)										
85.000	54.0	53.1	51.4	49.2	47.1	45.1	43.4	42.0	40.9	40.1
80.000	83.7	80.7	75.5	69.5	63.9	59.1	55.2	52.2	50.0	48.3
75.000	136.3	126.6	111.8	97.3	85.0	75.5	68.3	63.0	59.2	56.5
70.000	209.2	182.4	150.9	124.4	104.1	89.4	78.9	71.4	66.2	62.5
65.000	207.5	197.0	164.4	134.0	110.8	94.1	82.3	74.1	68.4	64.4
60.000	194.0	170.7	143.0	119.0	100.4	86.7	76.8	69.8	64.8	61.4
55.000	121.5	114.1	102.4	90.3	79.9	71.6	65.3	60.5	57.0	54.6
50.000	75.3	73.0	68.9	64.1	59.5	55.5	52.2	49.7	47.7	46.2
45.000	49.4	48.7	47.4	45.7	44.0	42.4	41.0	39.8	38.9	38.2
40.000	35.4	35.2	34.8	34.3	33.7	33.2	32.7	32.3	31.9	31.6

X (M)	31.000	34.000	37.000	40.000	43.000	46.000	49.000			
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Y (M)

85.000	39.5	39.1	39.0	39.0	39.3	39.8	40.6			
80.000	47.1	46.4	46.2	46.3	46.8	47.8	49.3			
75.000	54.6	53.5	53.1	53.3	54.2	55.8	58.2			
70.000	60.1	58.7	58.1	58.4	59.5	61.6	64.8			
65.000	61.8	60.3	59.7	60.0	61.2	63.4	66.9			
60.000	59.1	57.7	57.2	57.4	58.5	60.5	63.5			
55.000	52.9	51.9	51.5	51.7	52.5	53.9	56.1			
50.000	45.2	44.6	44.3	44.4	44.9	45.8	47.1			
45.000	37.7	37.4	37.2	37.3	37.5	38.0	38.6			
40.000	31.4	31.3	31.3	31.3	31.4	31.6	31.8			

4.2 TERMINATE THE RUN

MON DEC 15/80 09:27:08
CPU TIME USED SO FAR = 2 MINS 37 SECS

B30300